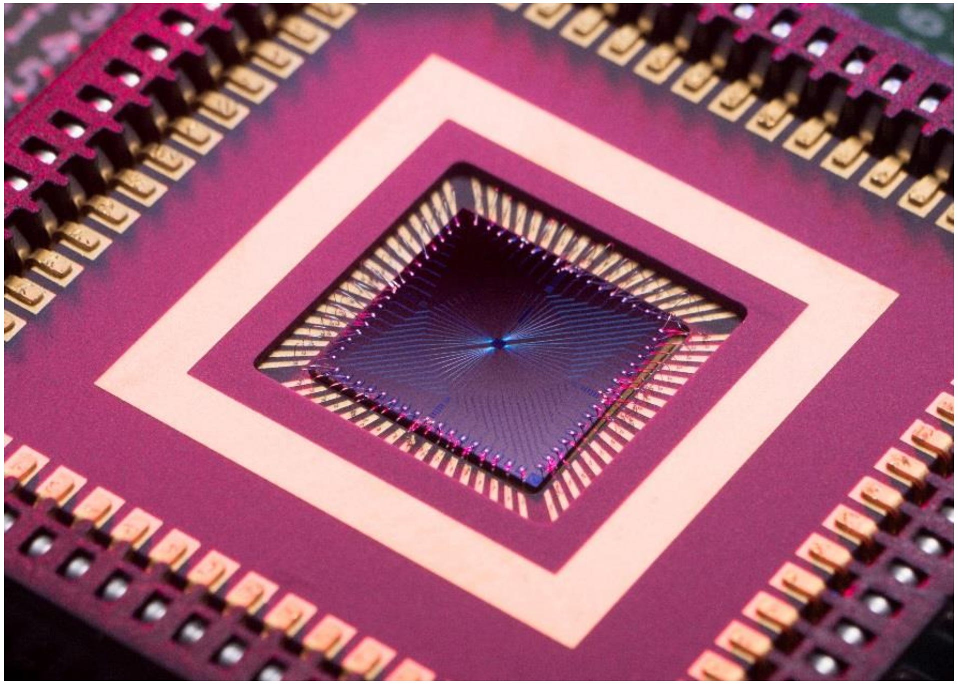
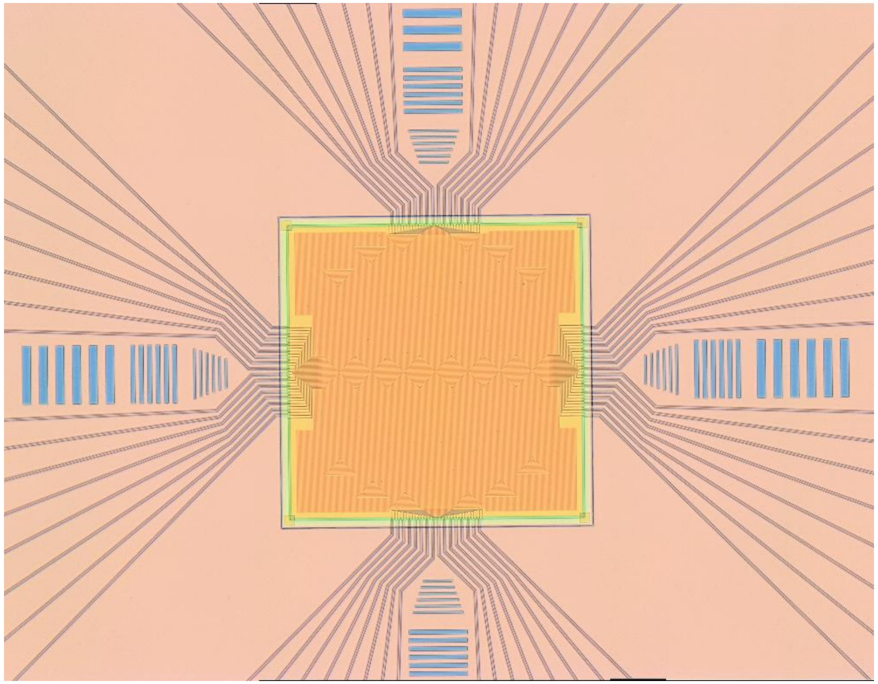
Superconducting Nanowire Single Photon Detectors for Optical Communication and Quantum Optics

Matt Shaw

APh 110 Seminar, 2 October 2017

Jet Propulsion Laboratory, California Institute of Technology

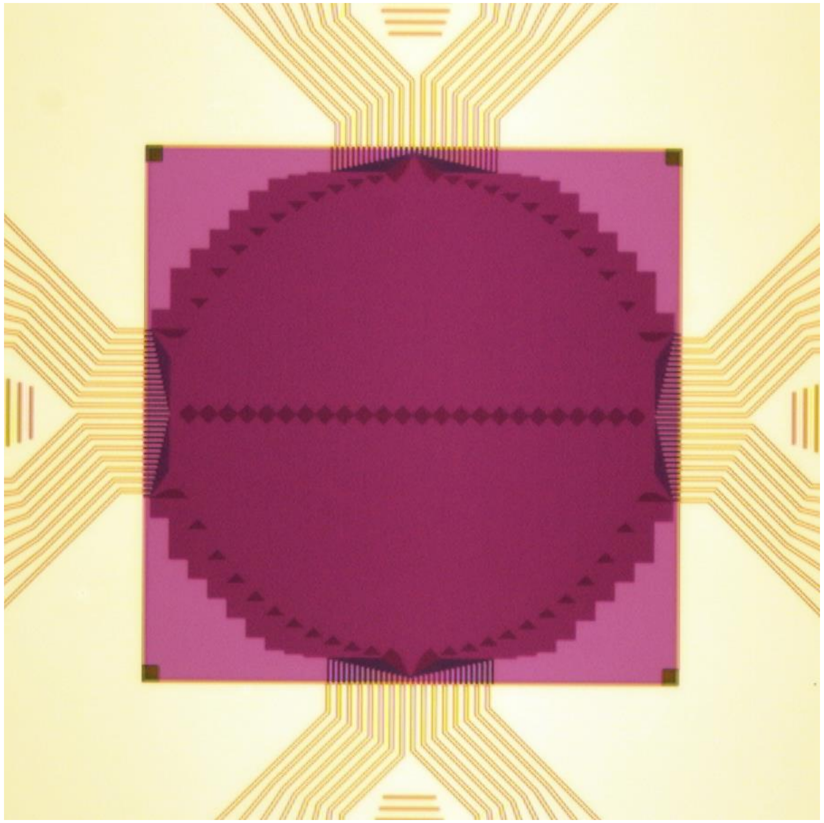


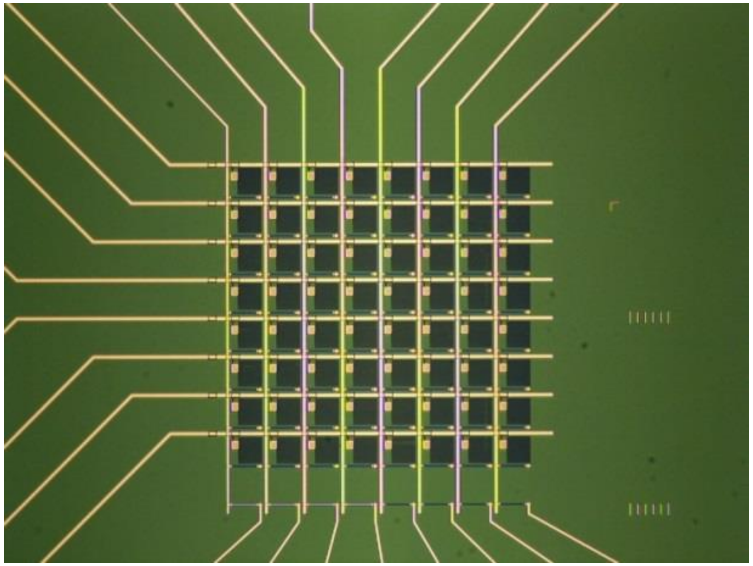


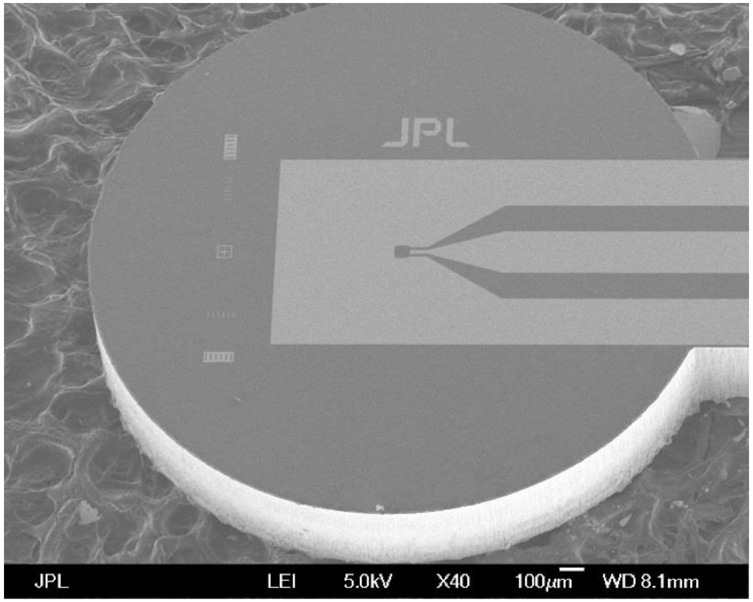
Research Group Overview

We develop **Superconducting Technology** to solve problems in single-photon detection

We use this technology to **enable new science**







JPL SNSPD Development Team

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California Institute of Technology

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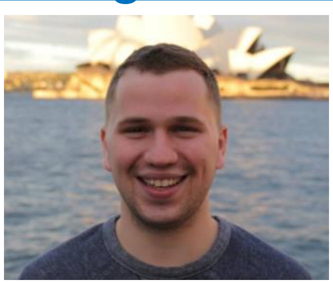
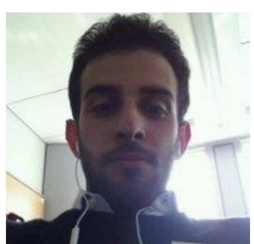
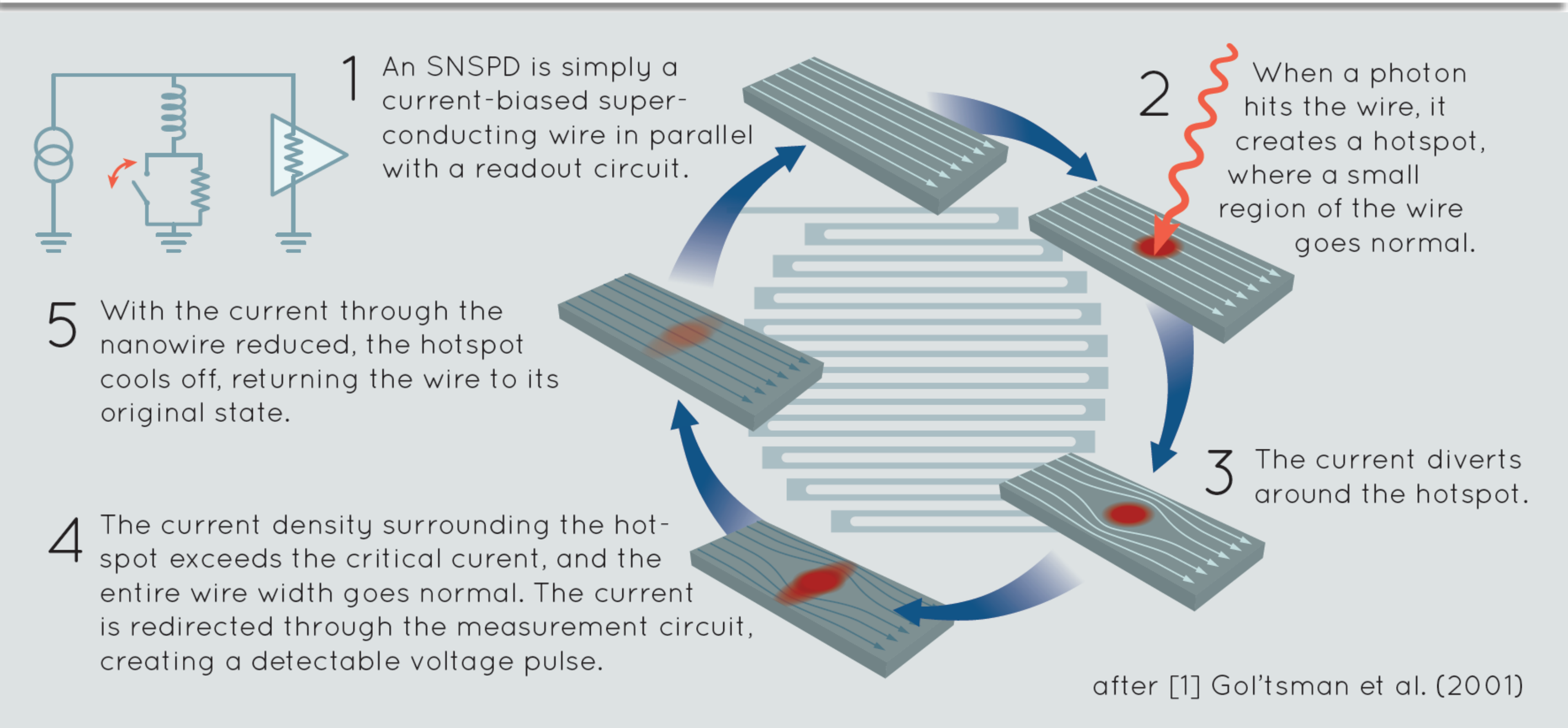

Eric Bersin


Simone Frasca


Eddy Ramirez

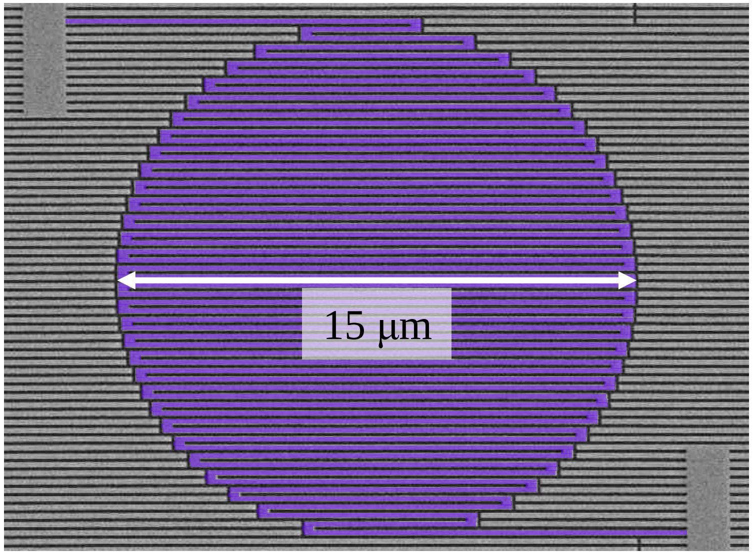
SNSPD Device Concept



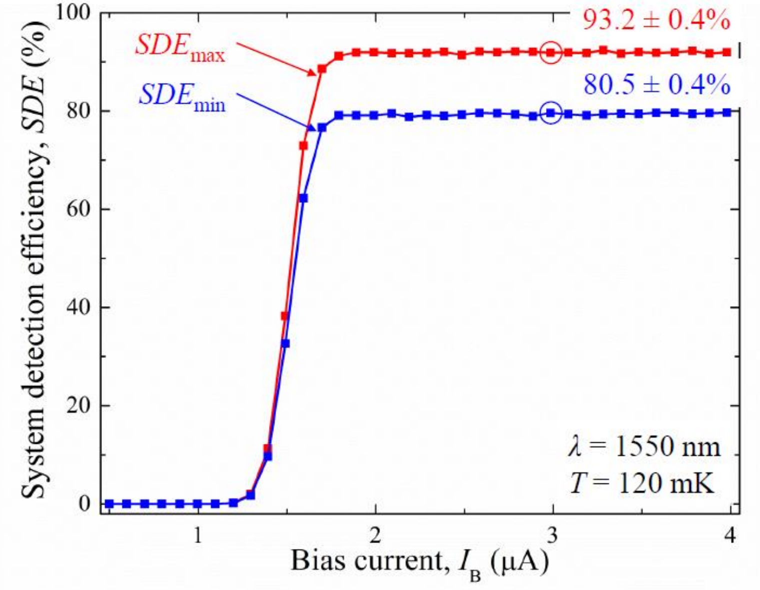
- Performance exceeds conventional detectors but requires cryogenic cooling (1-4 K)
- 16 years of active development (MIT / LL, NIST, JPL, Russia, Europe, Japan, China)
- SNSPDs are the highest performing detector for time correlated single photon counting

Tungsten Silicide SNSPDs

Superconducting Nanowire Single Photon Detectors

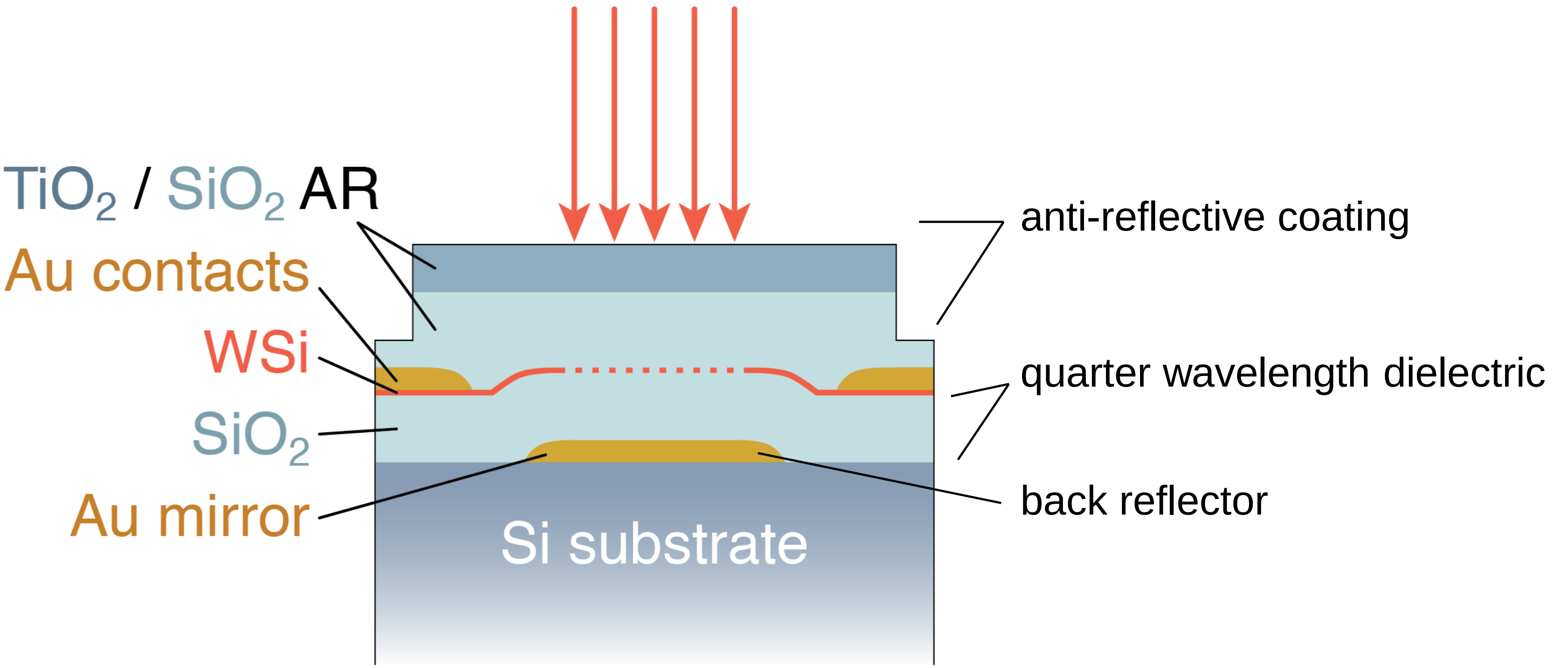


- Time correlated single photon counting, UV-5 μm
- > 90% efficiency at 1.5 μm
- < 100 ps time resolution
- Sub-Hz intrinsic dark rates
- 40 ns dead time
- Arrays as large as 64 pixels
- 1 K operating temperature
- Primary applications are space-based optical communication and quantum optics



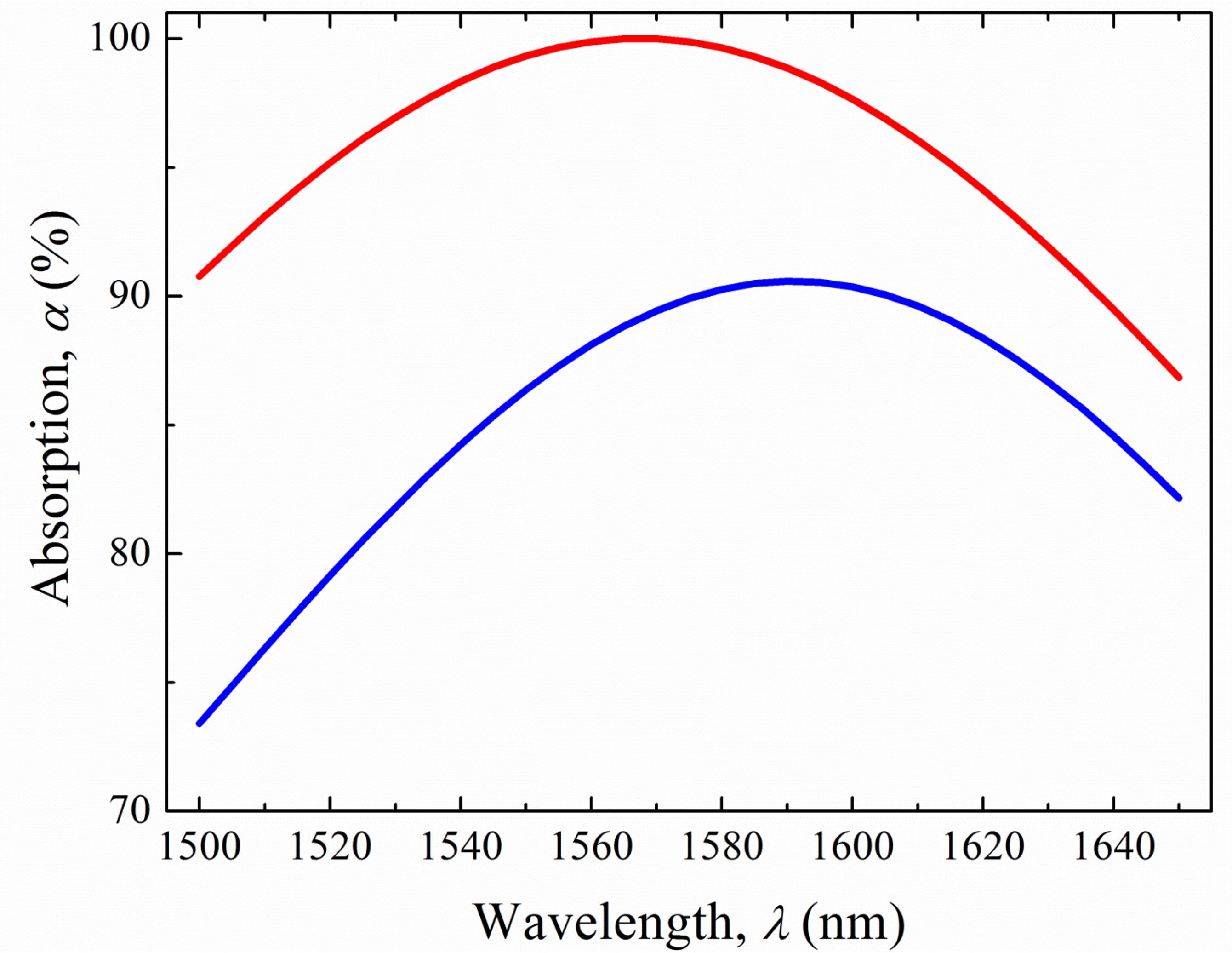
Marsili et al, *Nature Photonics* **7**, 210 (2013)

Optical Cavity to Enhance Absorption



- Photosensitive nanowire element is embedded in a vertical quarter-wave cavity
- Enhances detection efficiency from 20% to >90%
- Have optimized for high efficiency at 1550, 1310, 800, 373, 313 nm

Optical Stack for Enhanced Absorption



Self-aligned fiber coupling

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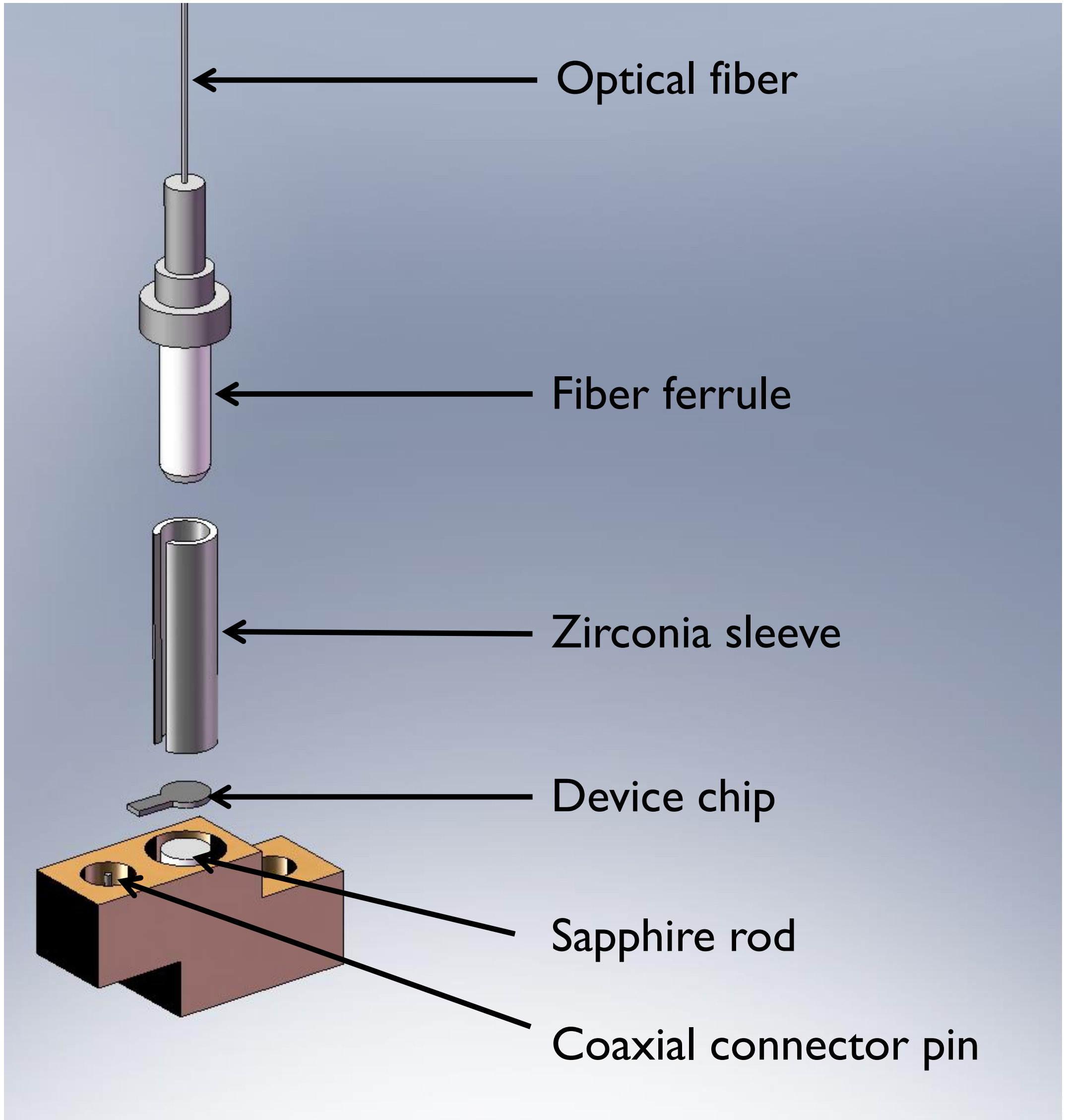
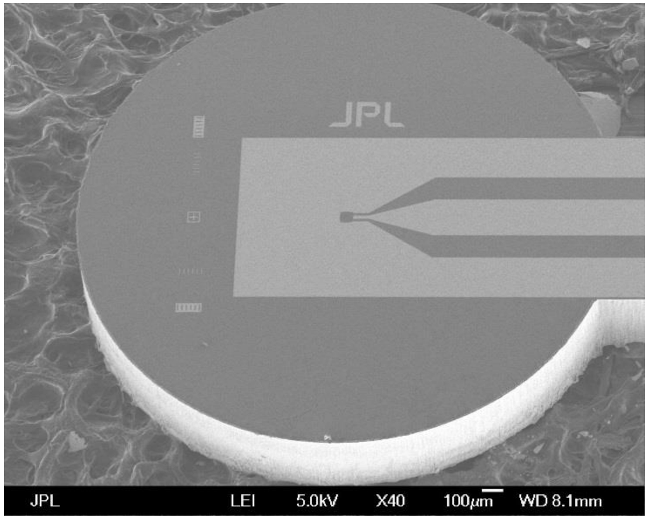
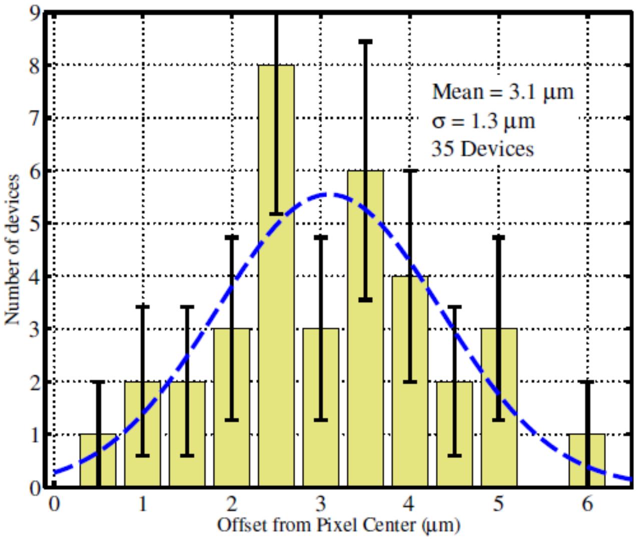
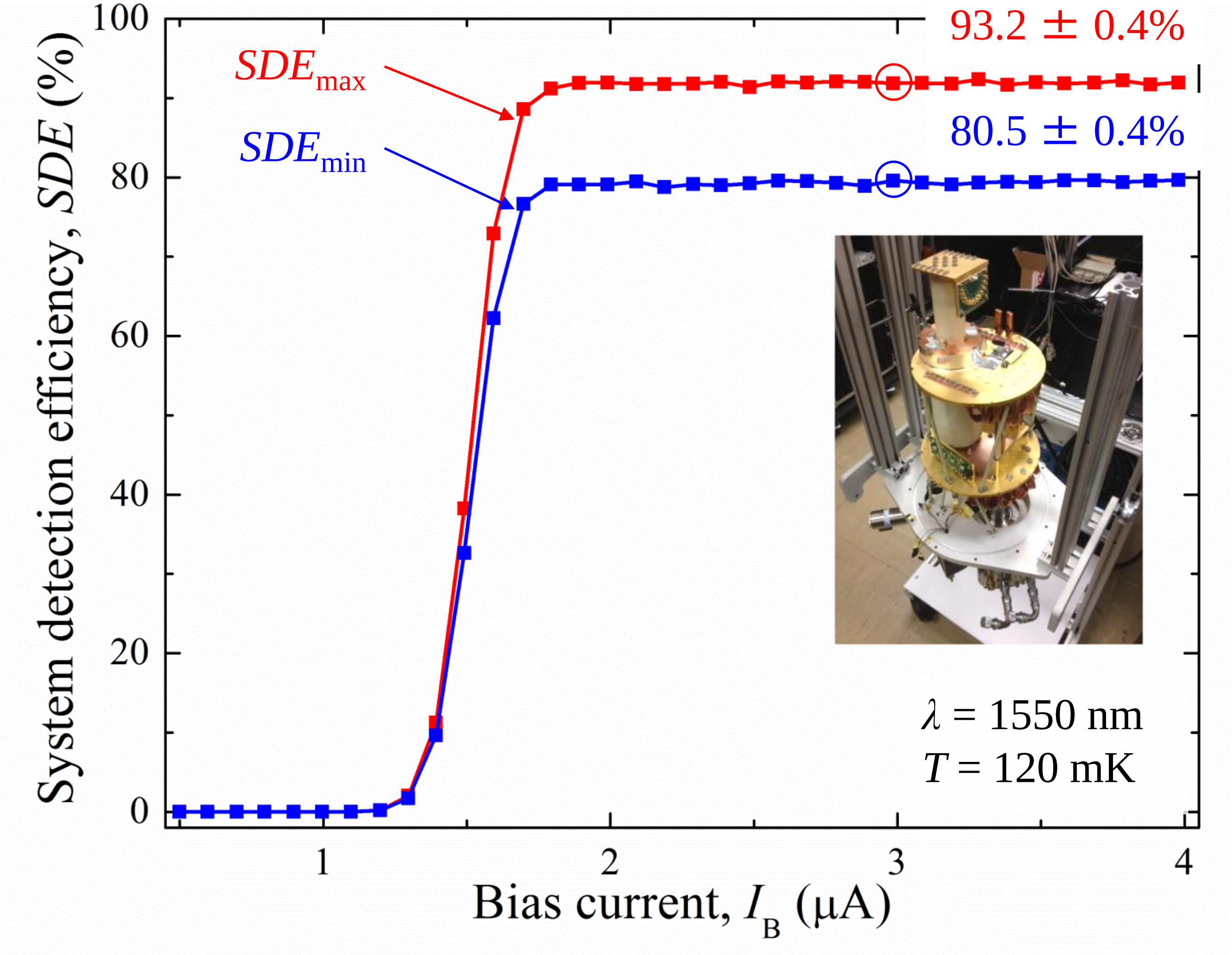




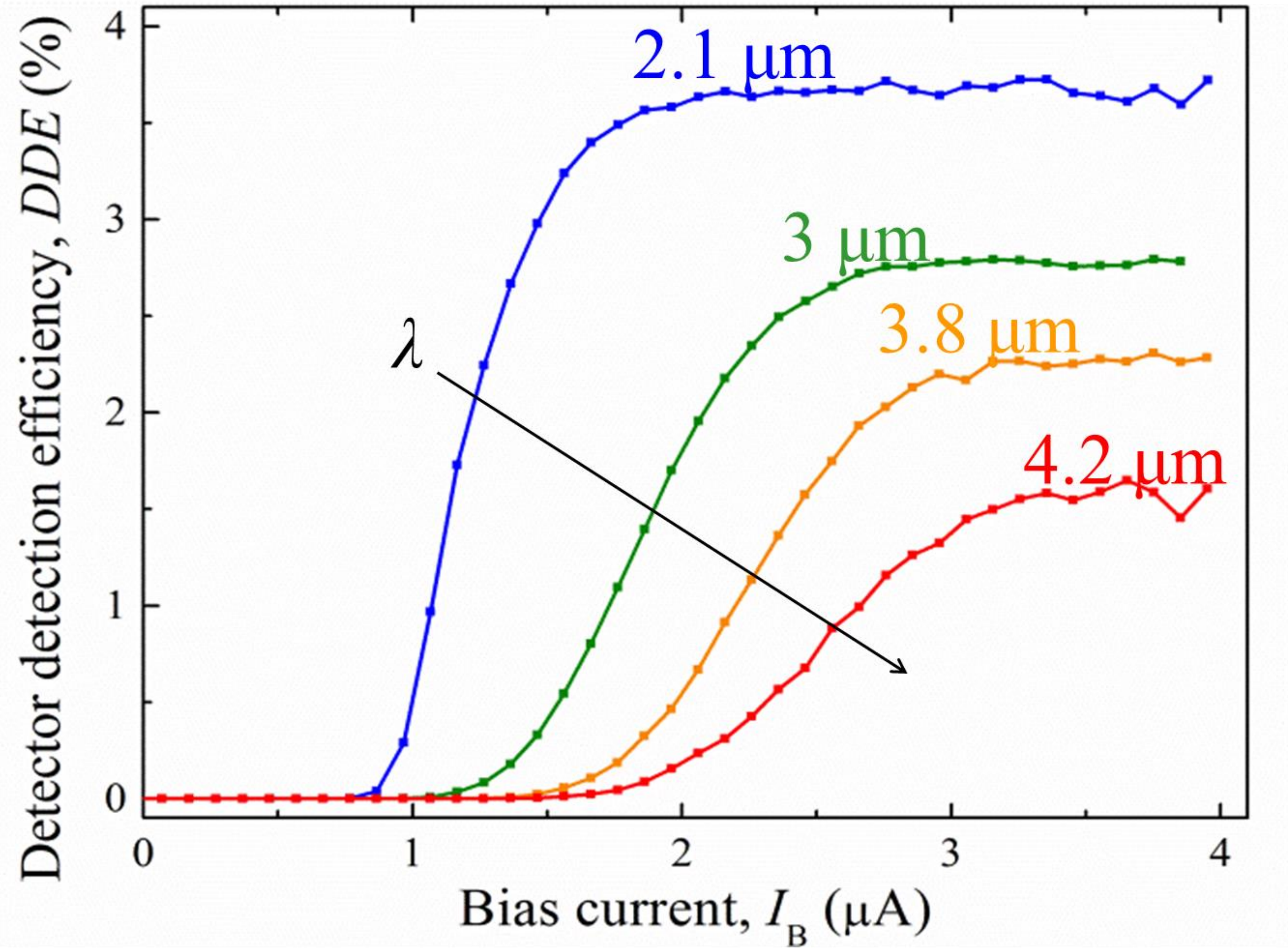


Miller et al., Opt. Express (2011)

93% System Detection Efficiency



Mid-IR Response



Overview of JPL SNSPD Development

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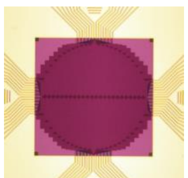
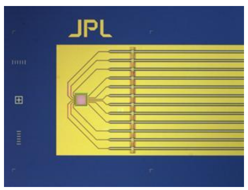
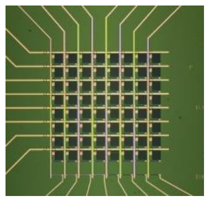
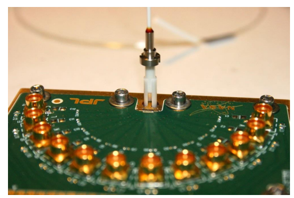
IR Arrays for Optical Communication

- 64 pixel arrays for DSOC ground terminal
- 12 pixel arrays for secondary LLCD ground terminal
- 64 pixel imaging arrays with row-column readout
- Fiber-coupled arrays for QKD
- Feasibility studies for future ISS teleportation concept

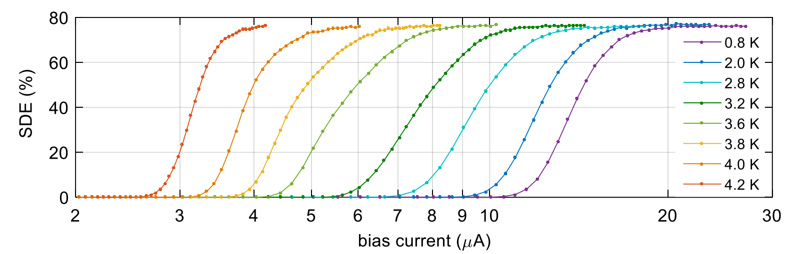



NASA STMD – NASA SCaN – DARPA

Ultraviolet SNSPDs

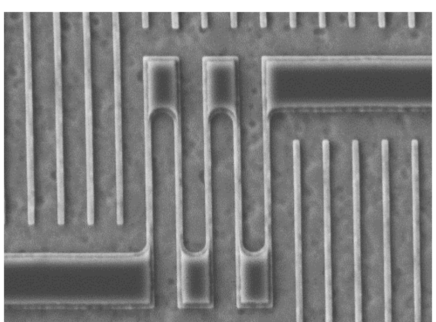
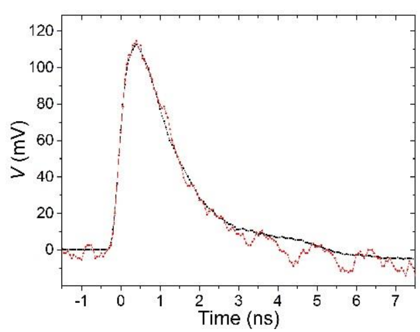
- UV SNSPDs for trapped ion quantum computing
- 80% efficiency at 370 and 315nm at 4.2 K
- Single photon sensitivity at 245nm
- Potential future applications in UV astrophysics



Other Government Agency

High Operating Temperature SNSPDs

- MgB2 SNSPDs single photon sensitive at 17 K
- Currently exploring YBCO SNSPDs w/ HeNeGa FIB

JPL, Other Government Agency

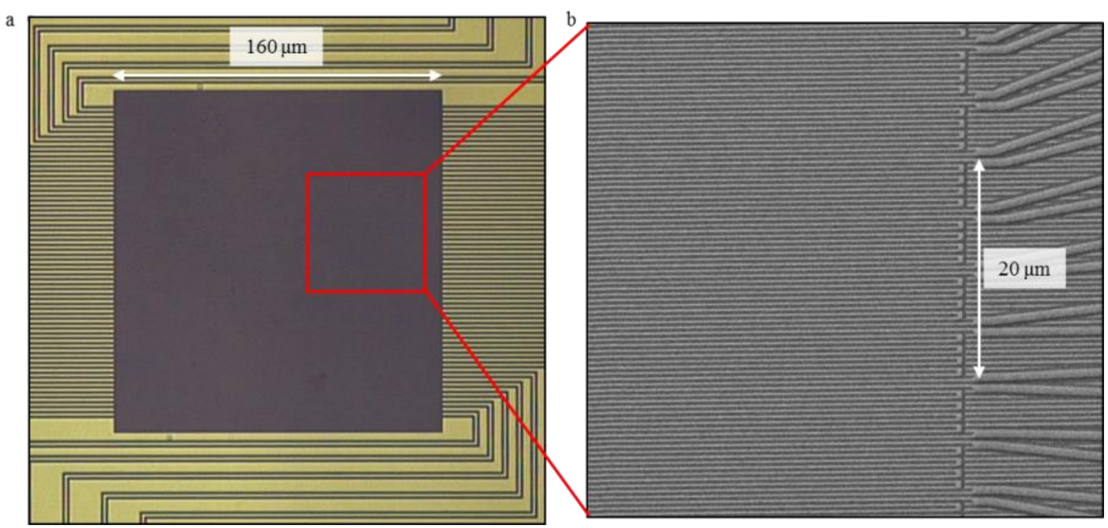
Fundamental Research

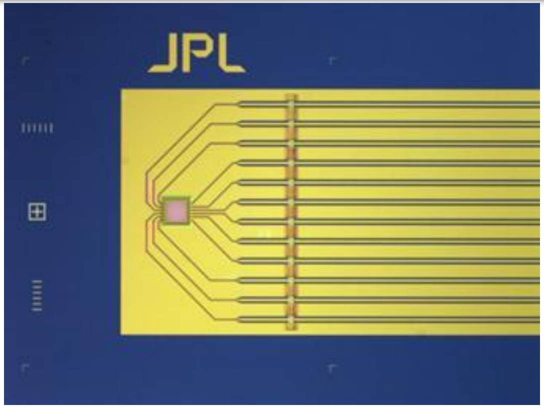
- Ultra-low jitter SNSPDs
- Frequency and time-domain multiplexing schemes
- Waveguide SNSPDs for integrated photonics
- Superconducting readout electronics
- Theory and device physics modeling
- New detector concepts and applications
- Collaboration with quantum optics groups

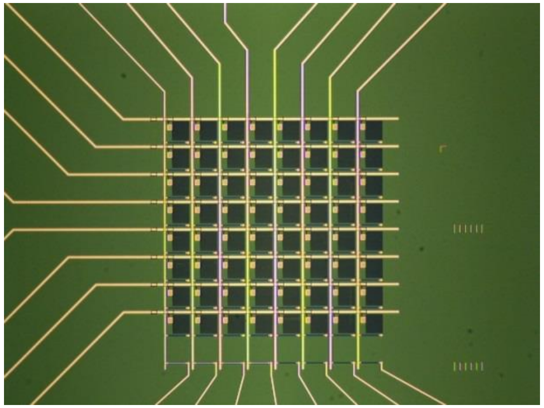
DARPA – JPL -- Caltech -- NASA STMD

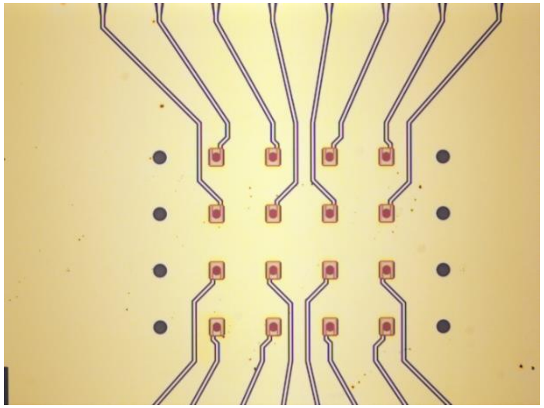
SNSPD Arrays

- Amorphous WSi permits scaling to large arrays
- Each pixel has essentially the performance of a single pixel fiber-coupled device
- Fiber-coupled vs free-space
- Non-imaging vs imaging
- Direct readout vs “row-column”
- Recently demonstrated up to 64 pixel arrays

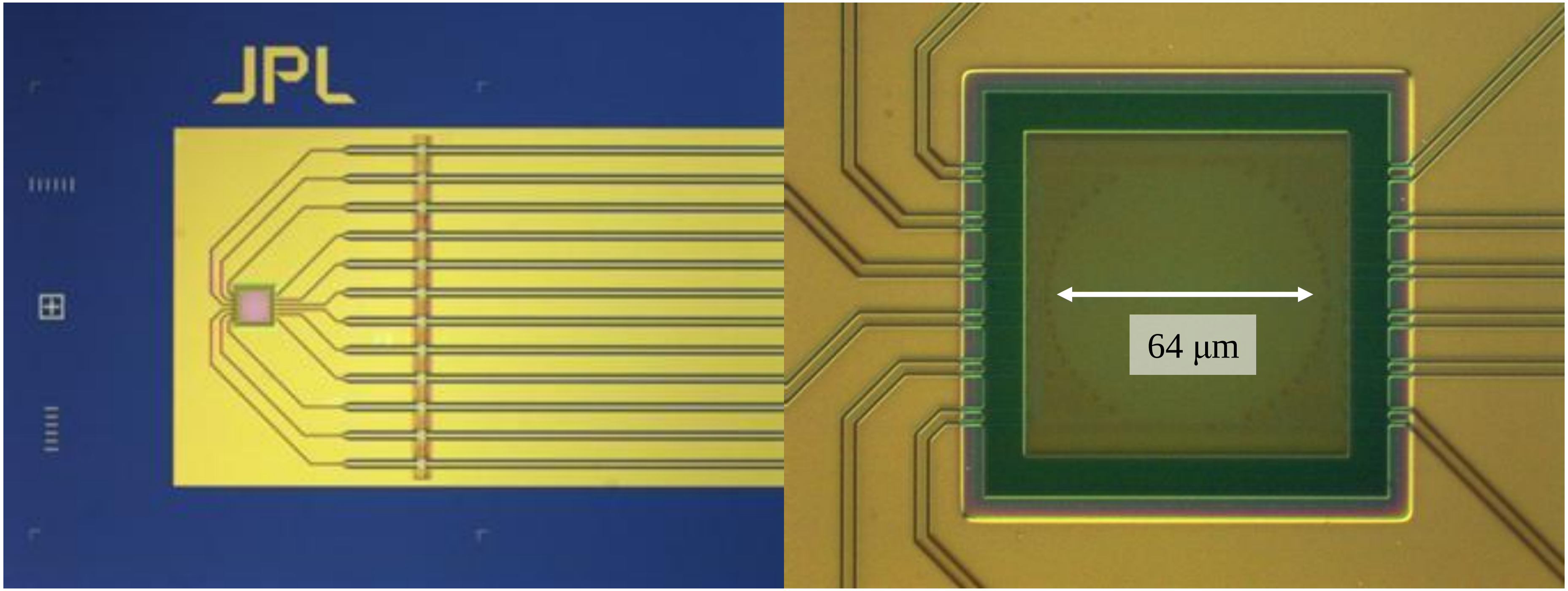






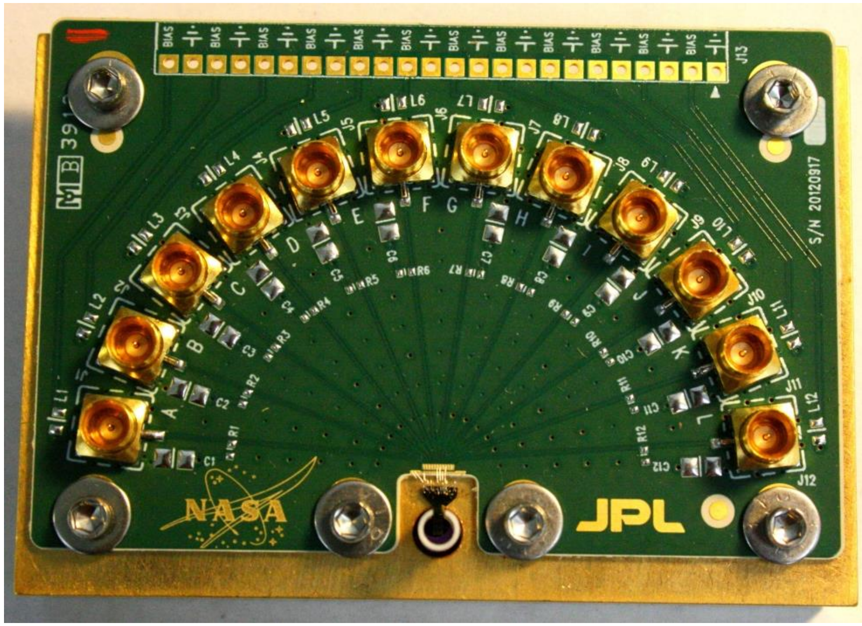


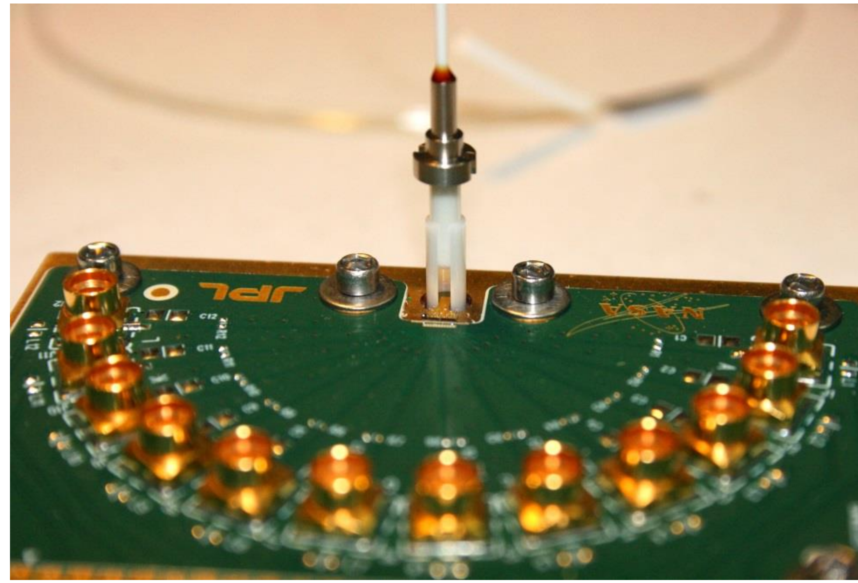
12 Pixel SNSPD Arrays

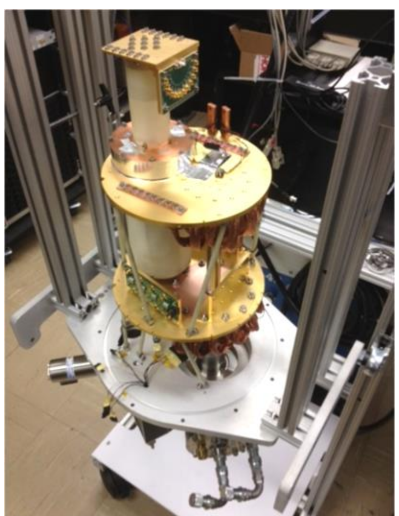


- Array design based on single-pixel SNSPDs described above
- 12 Counterbiased Nanowires, 6 wires in each plane, 160 nm width
- Designed for fiber coupling to 1-m OCTL telescope
- 64 µm diameter active area matched to GIF-625 multimode fiber
- Quarter wave optical cavity to resonantly enhance absorption at 1.55 µm
- ~40% total array efficiency
- Max count rate ~10 MHz / channel

12 Pixel SNSPD Array Packaging

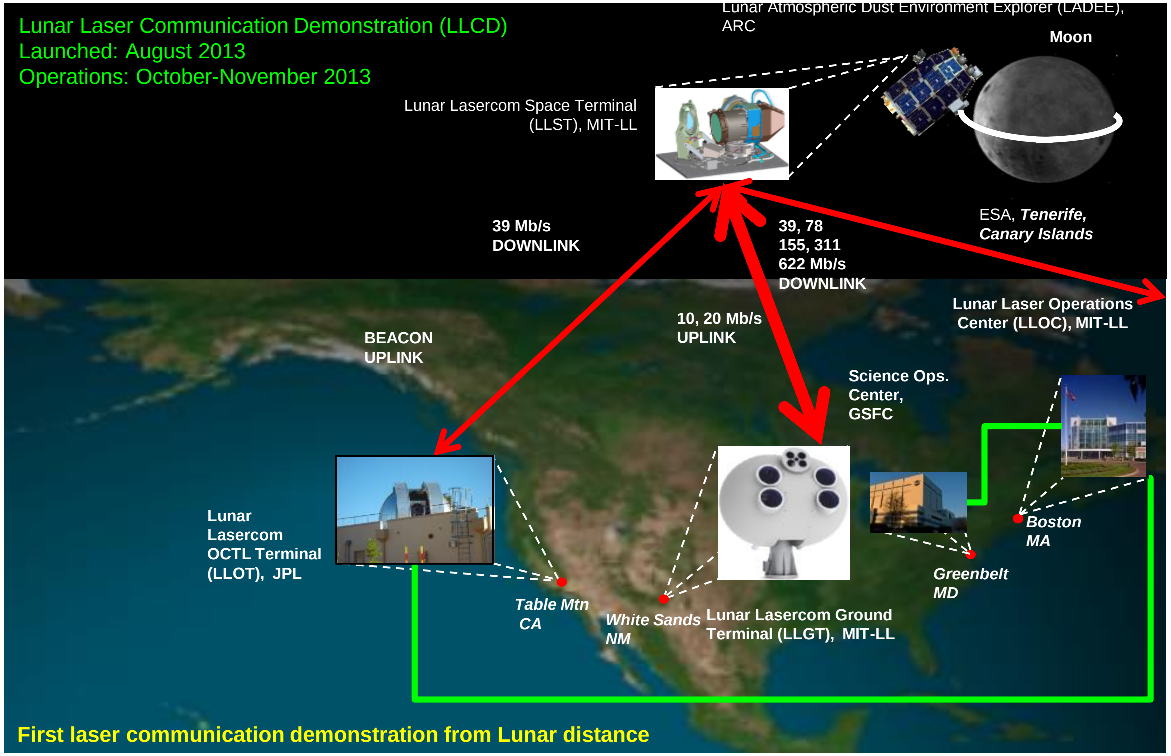






- Same self-aligned fiber coupling scheme is used
- Each wire is read out independently
- Operated in an 800 mK cryostat with fiber coupling

Field Demonstration: LLCD



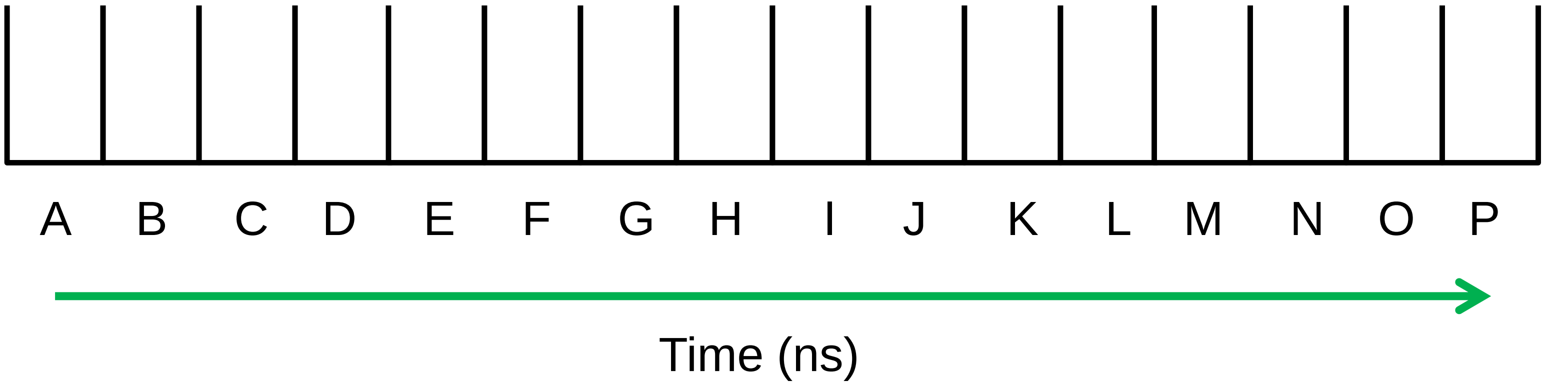
- Bidirectional laser communication demo from lunar orbit (400,000 km) at 1550 nm
- First demonstration of laser communication beyond earth orbit
- Uplink rates 10-20 Mbps, Downlink rates 39-622 Mbps
- Transmit Payload on LADEE Spacecraft (ARC) implemented by MIT-LL
- Managed by GSFC, Primary ground terminal implemented by MIT-LL
- Secondary ground terminals implemented by JPL and ESA

LLOT Reciever Overview

- **LLOT was a secondary ground station for the Lunar Laser Communication Demonstration (LLCD), located at Table Mountain, CA**
  - LLOT supported 20 LLST passes during October-November 2013
  - Received error-free downlink at 39 / 79 Mbps
  - Link support at Sun-Earth-Probe (SEP) > 10°
  - Transmit laser beacon to assist link acquisition
  - Transmit limited real-time channel and link diagnostics to operations center
  - Receiver implemented in software
  - 12-pixel WSi SNSPD detector arrays were operating at 800 mK.
  - SNSPD arrays were infused in ~January 2013, still very early stage technology

Pulse Position Modulation

- Data is encoded in optical pulse timing
- Ideal for “photon starved” applications such as deep space optical communication
- Send more data with less mass and power on the spacecraft
- LLST signals use PPM-16 encoding with 311 MHz – 5 GHz variable slot rate
- Scheme was recently used under DARPA InPho program to encode 13 bits/photon
- Requires detectors with high efficiency and sub-nanosecond time resolution



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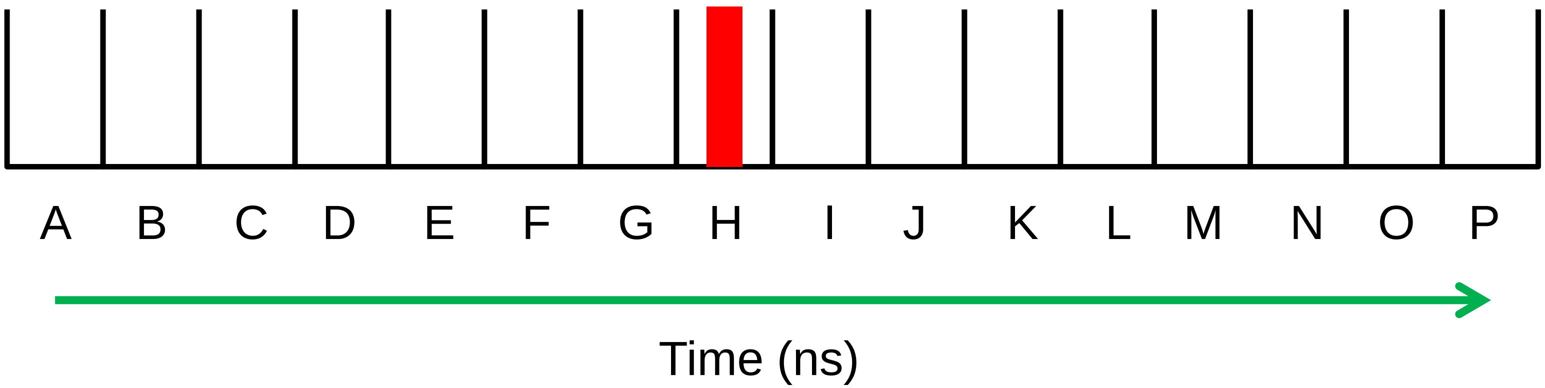

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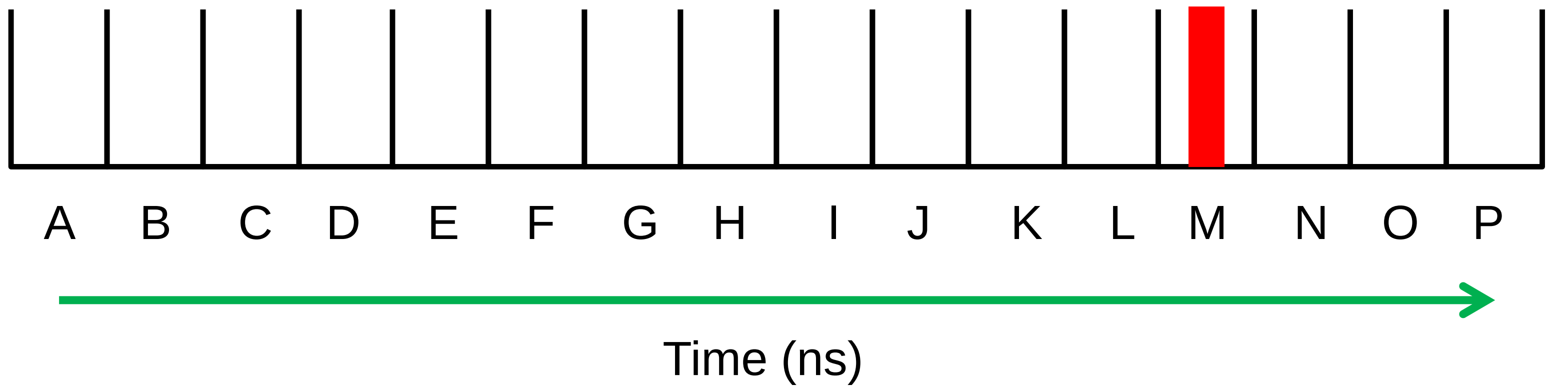
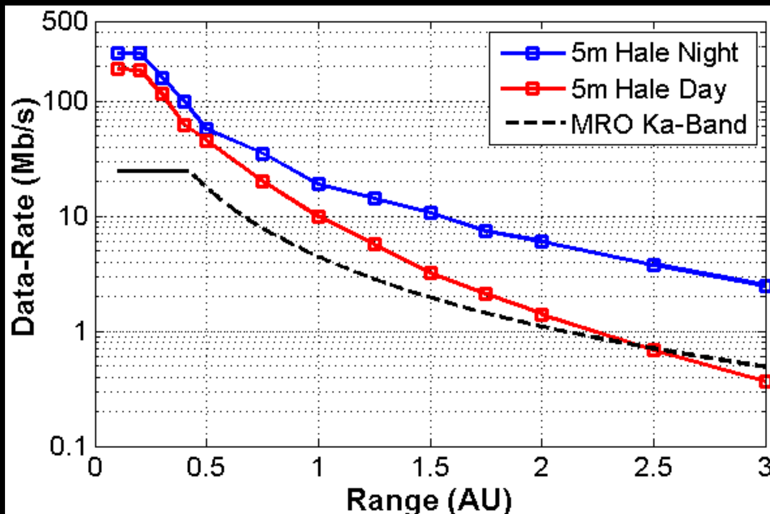
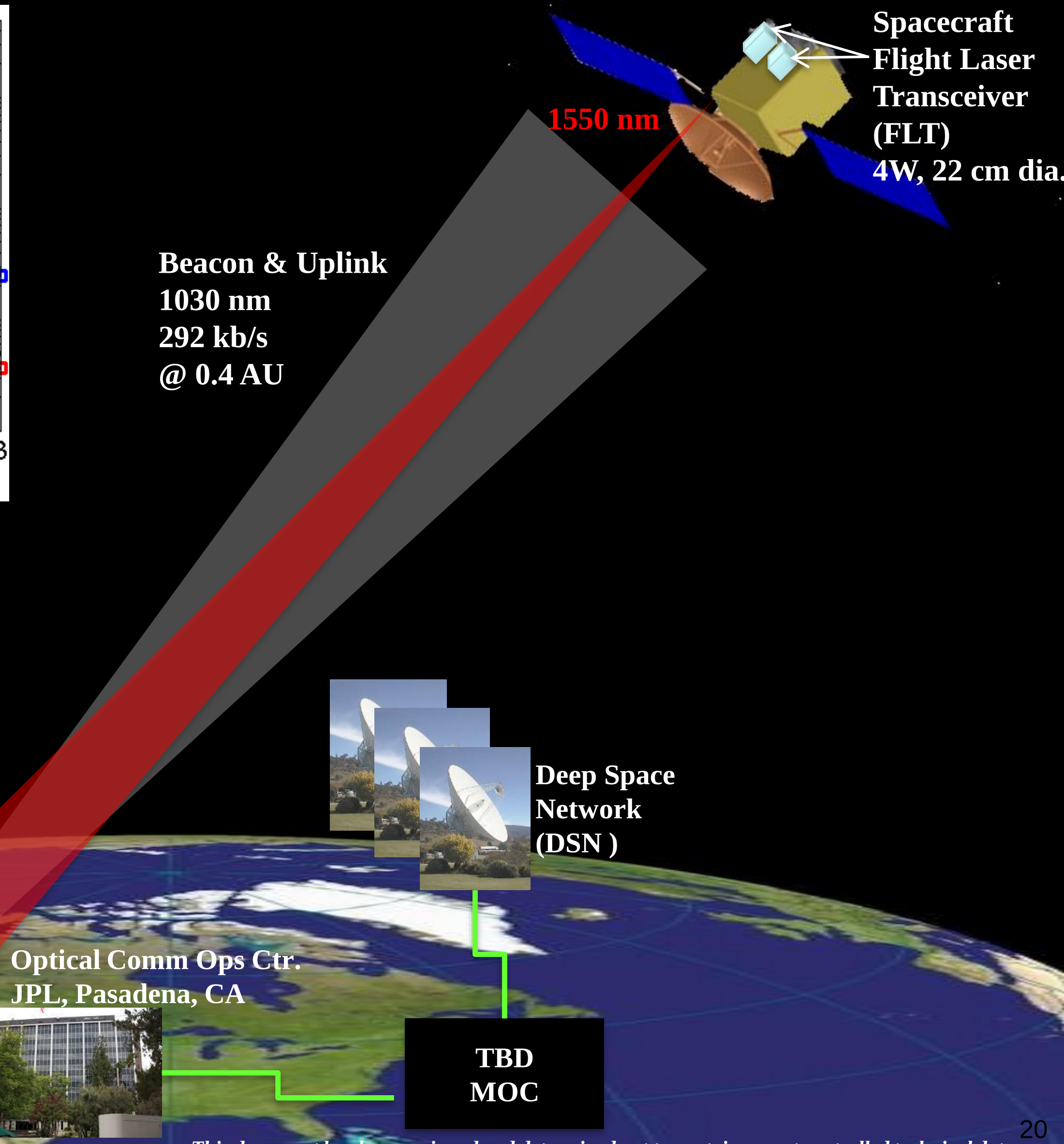


DSOC Tech Demo Mission

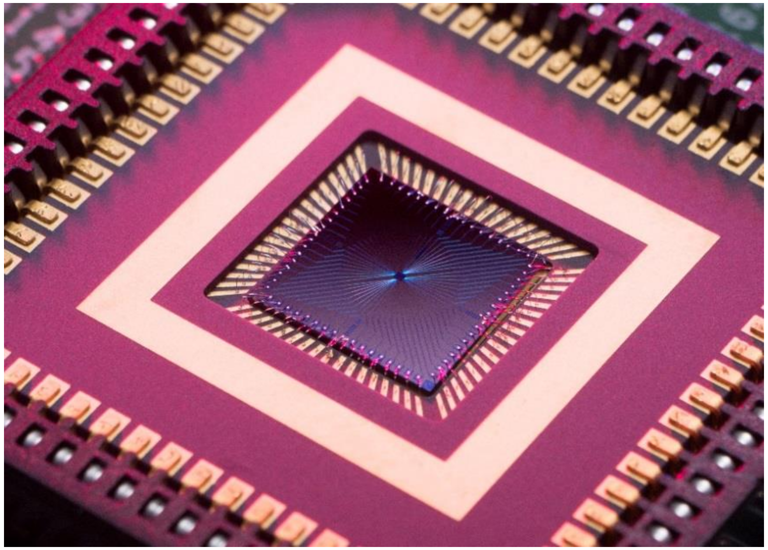


Performance using 4W average laser power w/22 cm flight transceiver to 5m ground telescope



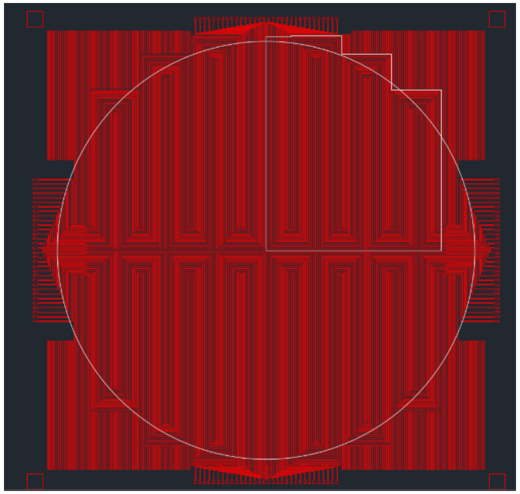
DSOC Project Overview

- Phase A of NASA Technology Demonstration Mission
- Flight terminal planned to launch on PSYCHE mission in 2022
- Projected downlink data rates from 200 kbps - 265 Mbps
- PPM 16 – 128, 500 ps – 8 ns slot widths, 4 slot intersymbol guard time
- Developing a 320-µm 64-pixel WSi SNSPD array for the ground receiver

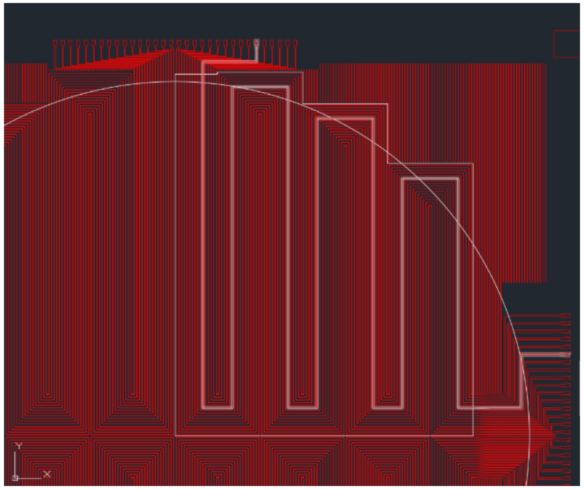


64-Pixel SNSPD Array

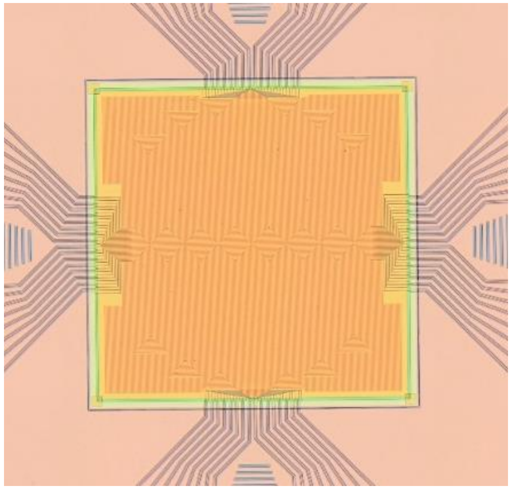
- 64-pixel WSi SNSPD array embedded in optical cavity optimized for 1550 nm
- 320-µm dia. free-space coupled active area, 4 quadrants, 16 co-wound wires per quadrant
- 13.3% nanowire fill factor: 4.5 x 160 nm wires on a 1.2 µm pitch
- Two-layer AR coating to enhance efficiency at low fill factor: 73% system detection efficiency
- 62 out of 64 measured nanowires show bias plateau
- Full 64-channel readout system and 64-channel time-to-digital converter



CAD Design of SNSPD focal plane array



CAD Design showing one of 16 individual sensor elements per quadrant



Optical microscope image of SNSPD array

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Project Goals and SNSPD Performance

	DSOC Goals	Progress to date	Capability Achieved
Detection Efficiency	>50% minimum >70% desired	93% (fiber-coupled single pixel) 73% (Free Space, 320 μm array)	✓
Timing Jitter	230 ps (FWHM)	80 - 120 ps (SNSPD array) 200 – 250 ps (with TDC)	✓
False Counts	< 1 Mcps total free space coupled	0.35 – 3.8 Mcps (320 μm array)	✓
Maximum Count Rate	830 Mcps (264 Mbps, 0.2 AU, night cruise)	465 – 1160 Mcps (SNSPD array) ~600 Mcps (with TDC)	✓
Active Area	260 μm diameter (35 μrad seeing, Palomar daytime)	320 μm diameter (50 μrad seeing, Palomar daytime)	✓
Numerical Aperture	f/1.2	f/4	

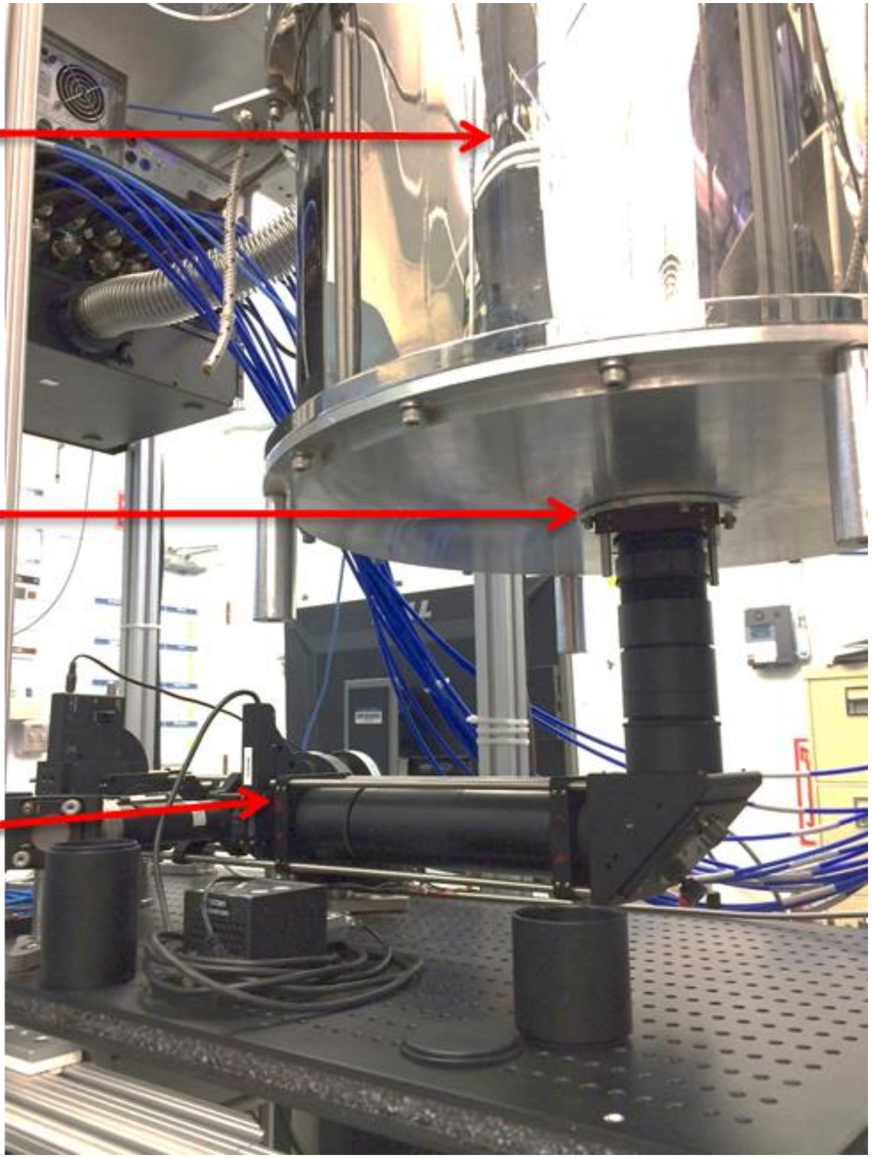
1550 nm operating wavelength

Free space coupled

1 K operating temperature

Free Space Coupling

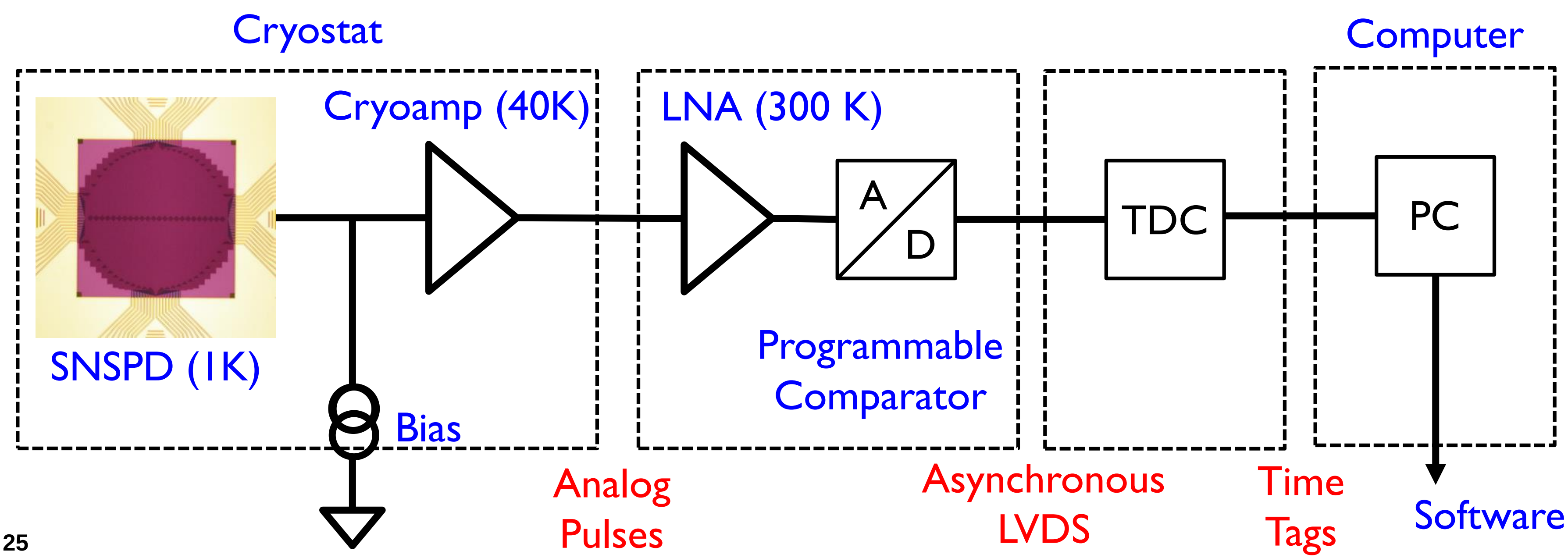
- Efficient coupling to large apertures requires free space coupling with cryogenic lens
- 300 K BK7 vacuum window
- 40 K, 4 K BK7 filters to block thermal background
- Engineering tradeoff between efficiency and false counts
- Experimenting with cryogenic spectral and spatial filters
- Must consider finite numerical aperture of detector



SNSPD Array Readout Architecture

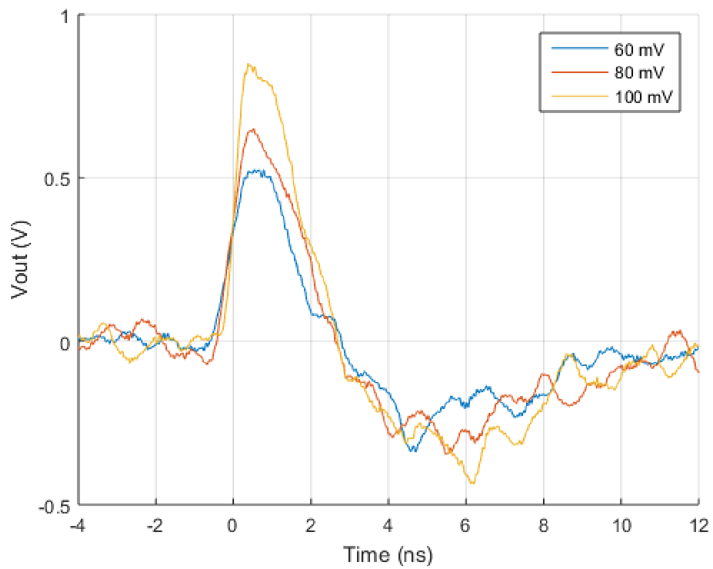
- Direct readout of 64 channels into an FPGA
- Brass flex circuits from < 1 – 40 K
- DC-coupled cryogenic amplifiers
- Copper flex circuits from 40 - 300 K
- Room temperature amplifiers and comparators
- FPGA-based time tagger
- Currently setting up SNSPD optical communication testbed

16-channel brass RF flex circuit

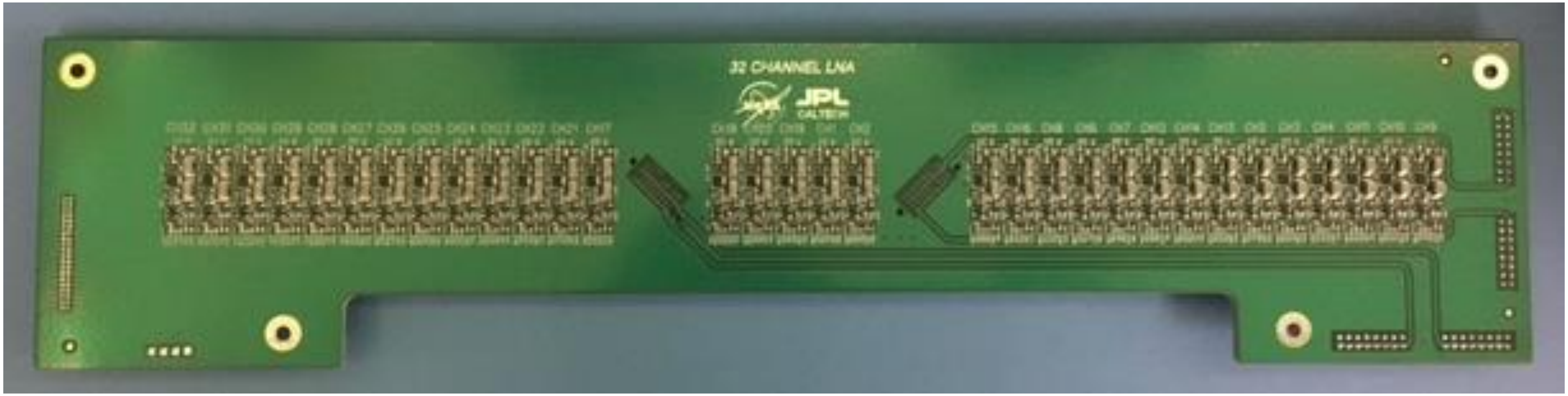


DC Coupled Cryogenic Amplifiers

- 2x 32-channel amplifier boards operated at 40 K
- 32 dB total gain
- Low-cost commercial cell phone components
- RFMD SGL-0622z cryogenic RF amplifier
- Broadcom ATF-35143 Psuedomorphic HEMT
- DC coupled with 50 ohm terminated input
- Detector bias added on amplifier board



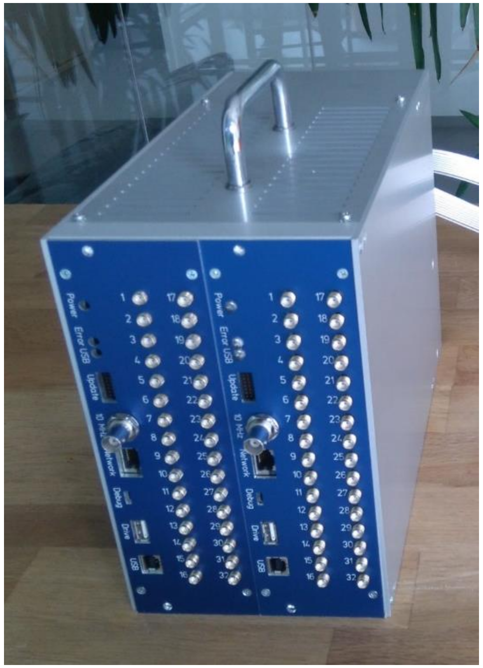
SNSPD output pulses at different bias points



32-channel cryogenic amplifier board, operated at 40 K

Time to Digital Converter Development

- Asynchronous time tagging receiver approach
- Need to tag photon arrivals across 64 channels with high time resolution
- Need to stream data into receiver FPGAs at ~ gigatag / second count rates
- Streaming 64-channel TDC currently under development through commercial partners
- Prototype TDC can fill 512 Mtag buffer at rates up to 600 Mtps w/ 166ps resolution



Efficiency Measurements

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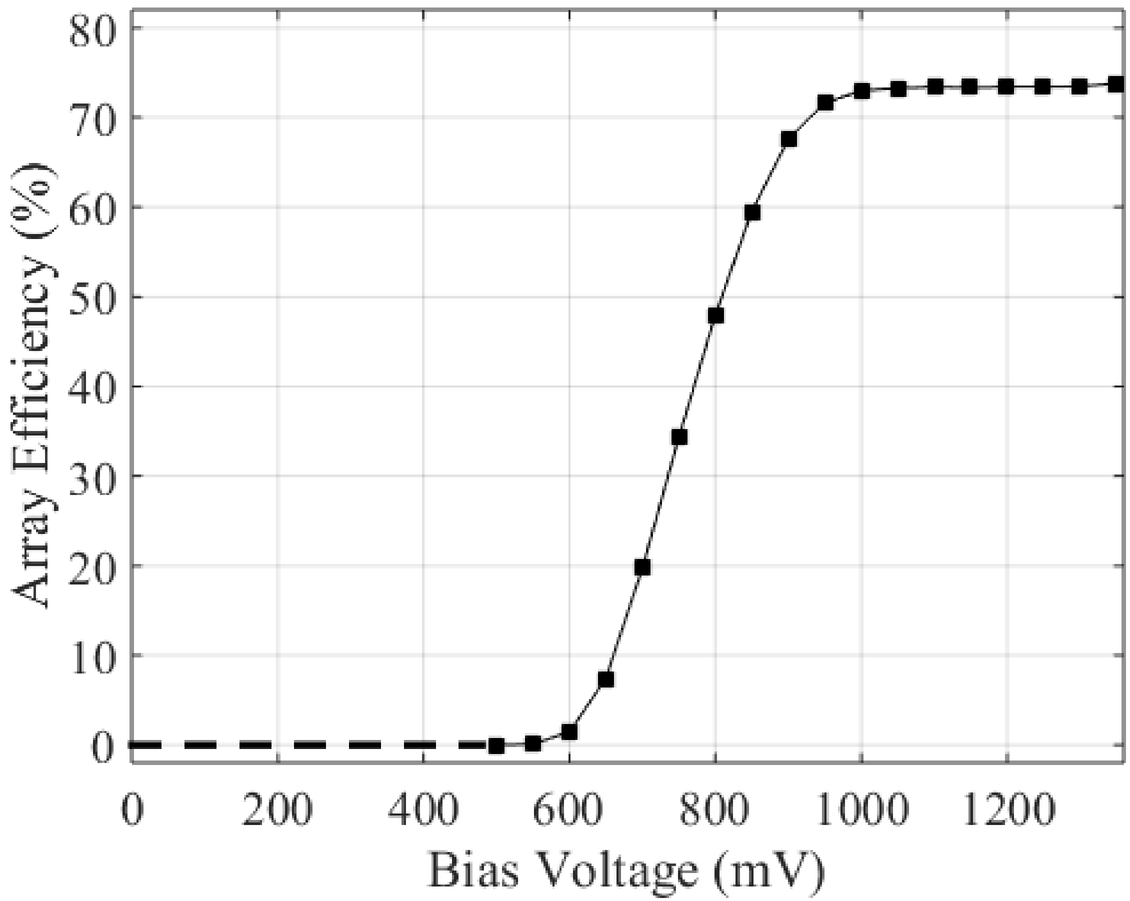
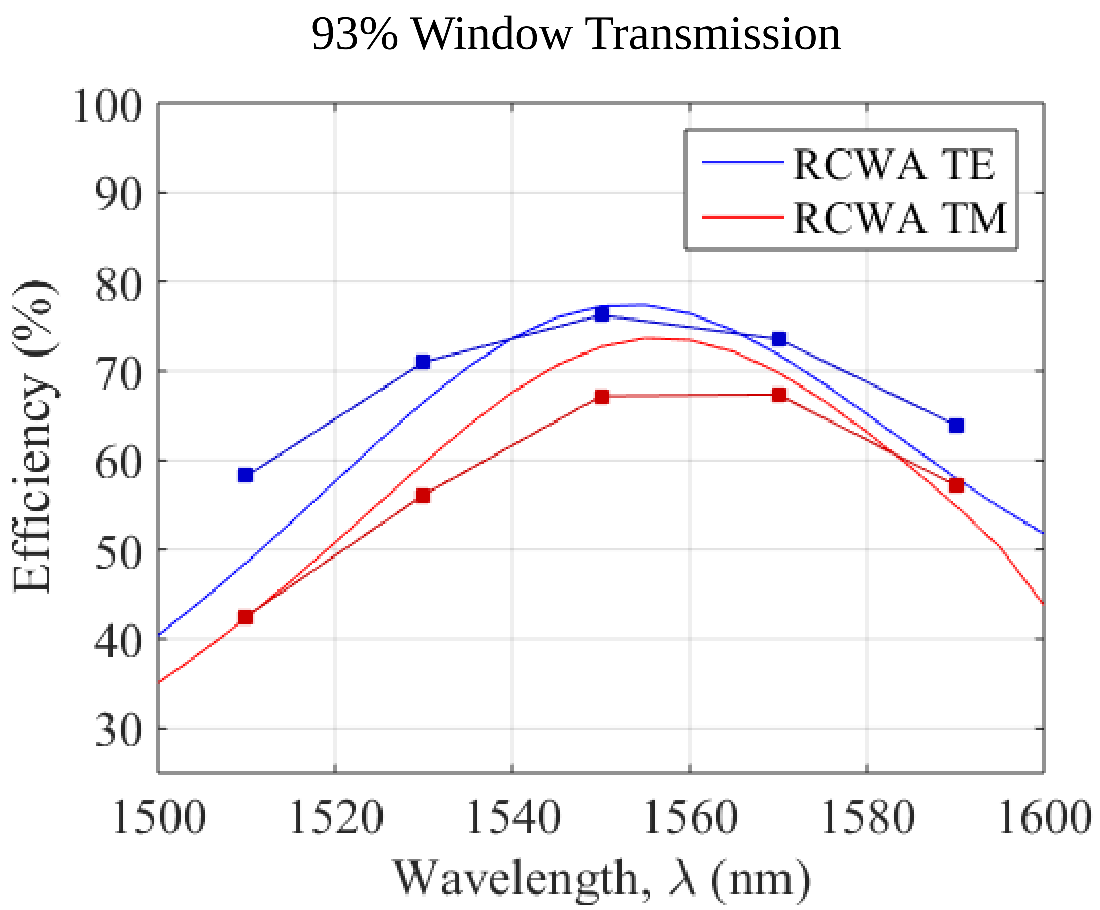


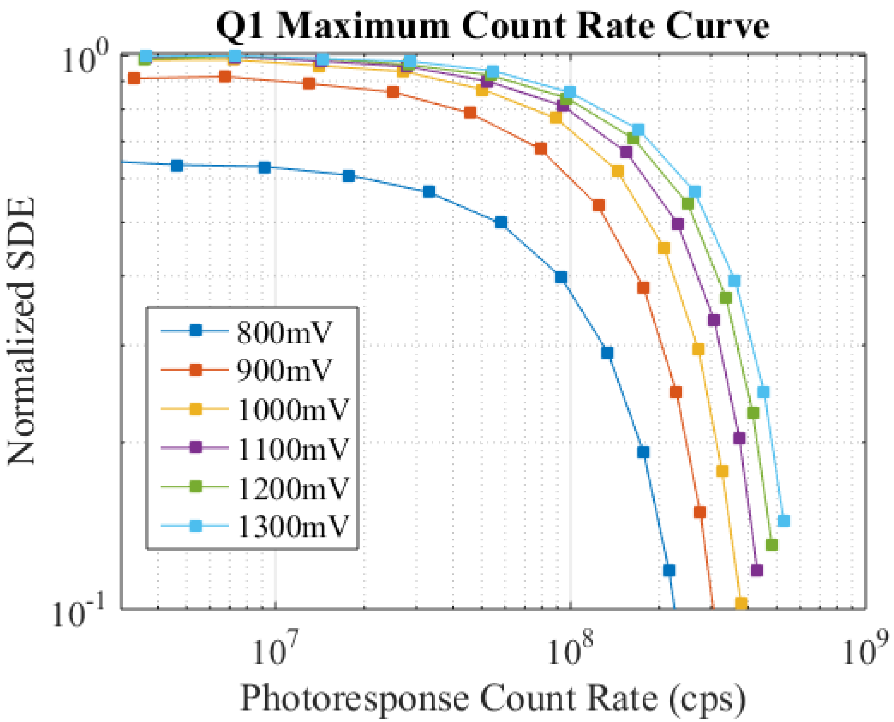
- System detection efficiency measured through cryostat window, 40K and 4K IR filters
- Measured SDE by focusing 50 um spot into one half plane (32 channels)
- Measured 73% efficiency in TE polarization at 1550 nm, 65% in TM

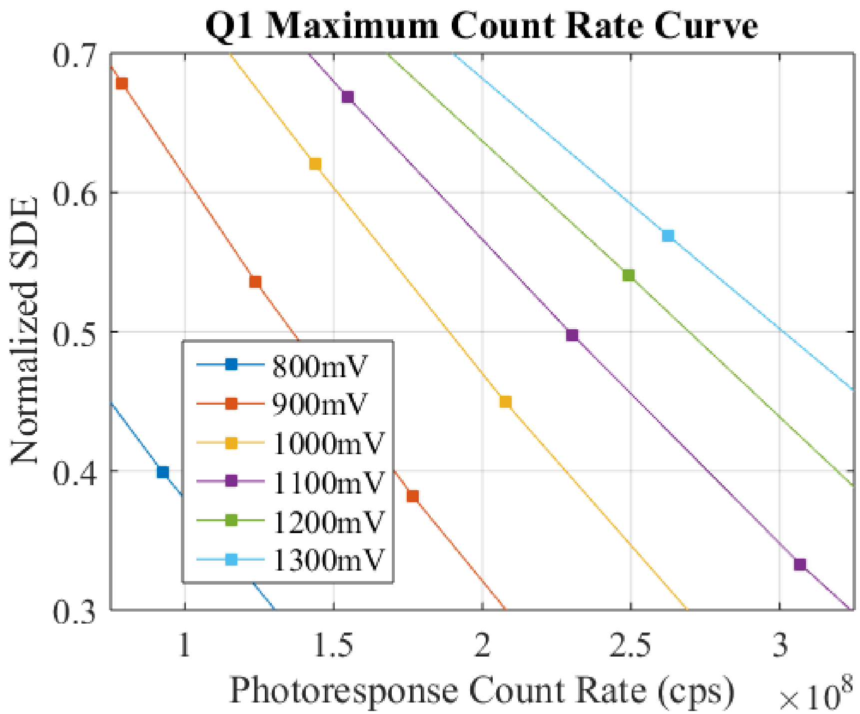
Efficiency Measurements

- Cavity is well centered near 1550 nm
- Efficiency matches RCWA simulation assuming 93% total transmission (97.6% per window)



Maximum Count Rate





- MCR measured with beam centered on a single quadrant due to count rate limitations in TDC
- 120 – 300 Mcps 3dB point per quadrant
- Scales to 465 – 1160 Mcps across 62 pixels

Device Timing Jitter

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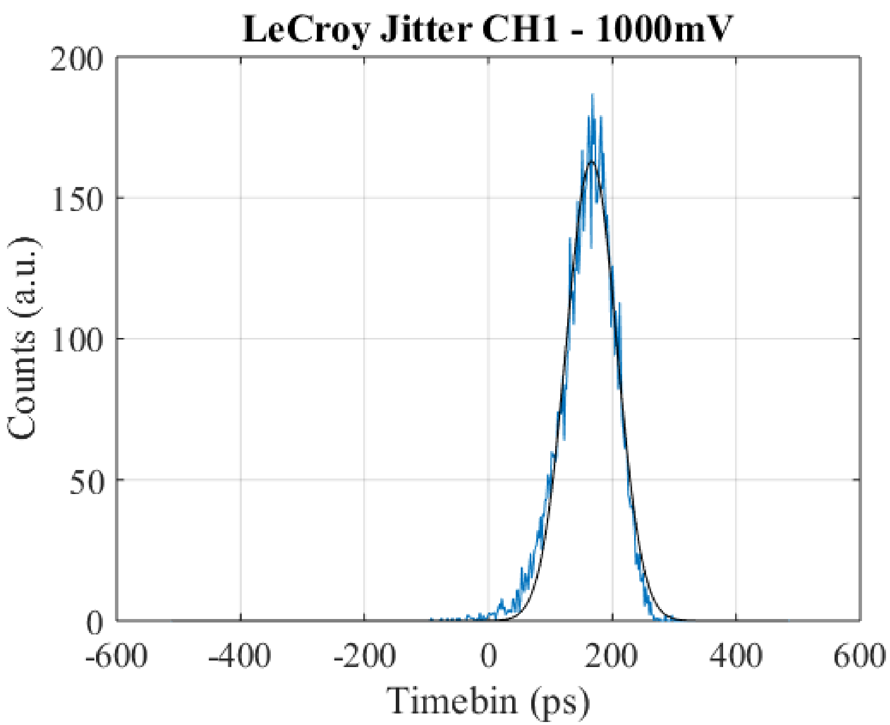
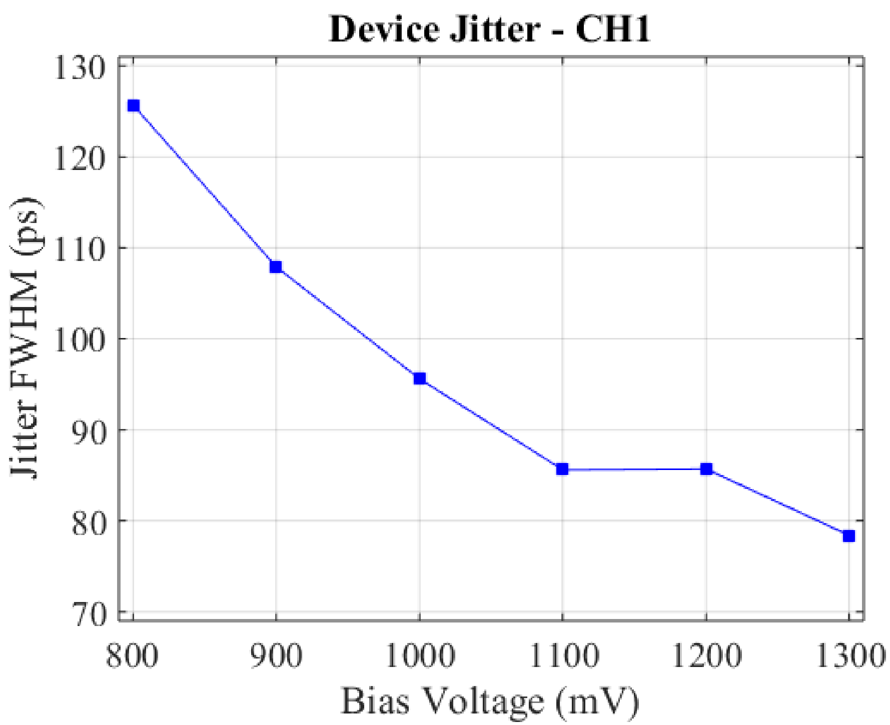
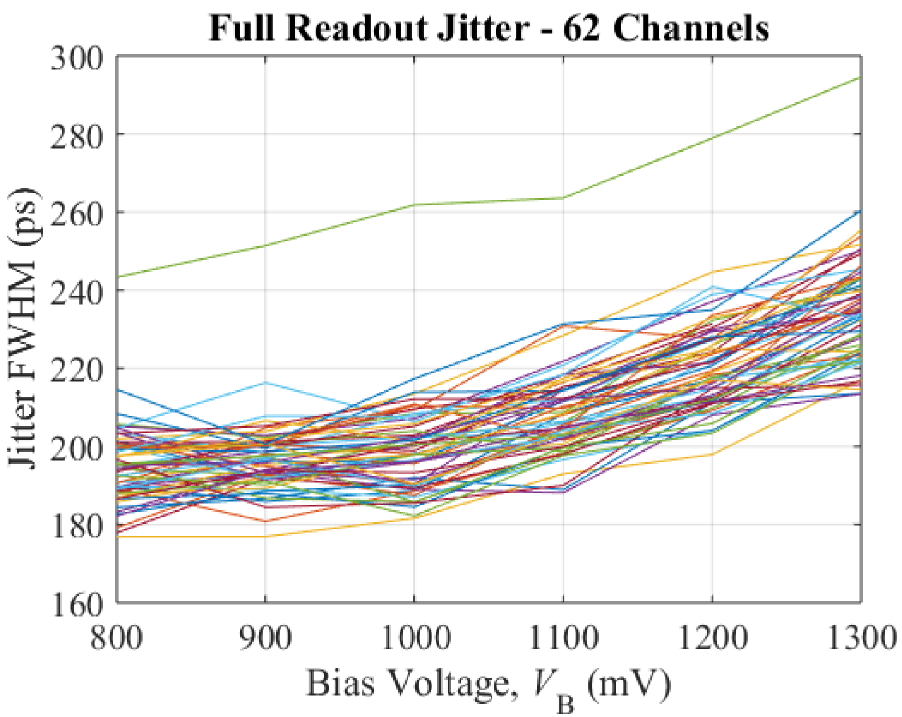
- Representative individual pixel timing jitter measured using mode-locked laser and oscilloscope
- IRF is close to Gaussian
- 125 – 79 ps FWHM

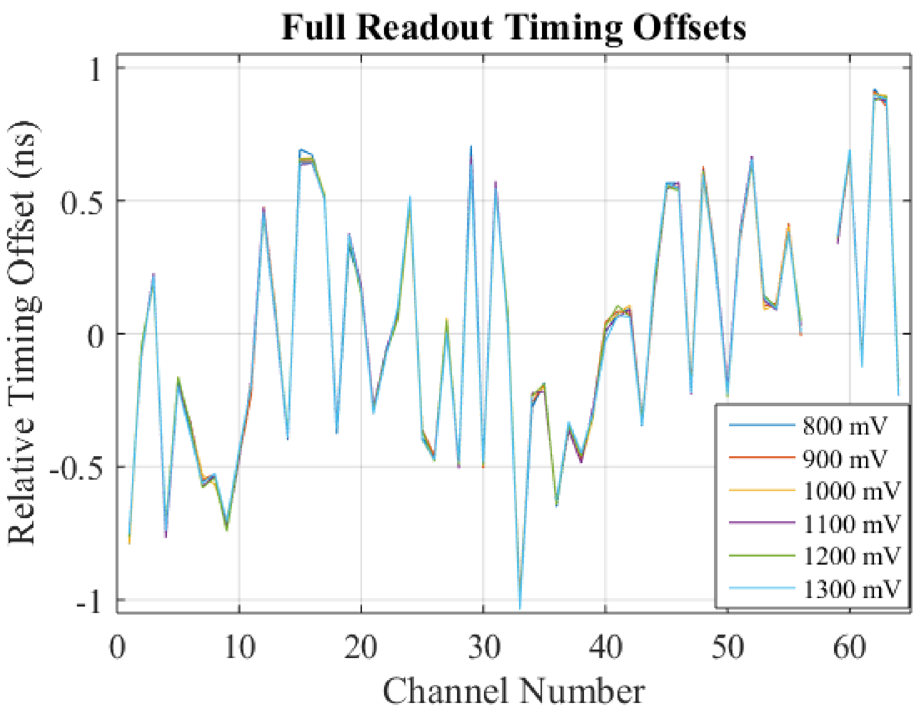




System Timing Jitter

- Full system timing jitter is typically below 250 ps FWHM
- Dominated by jitter in FPGA-based time-to-digital converter
- Timing offsets between channels are due to imperfect length matching in readout chain

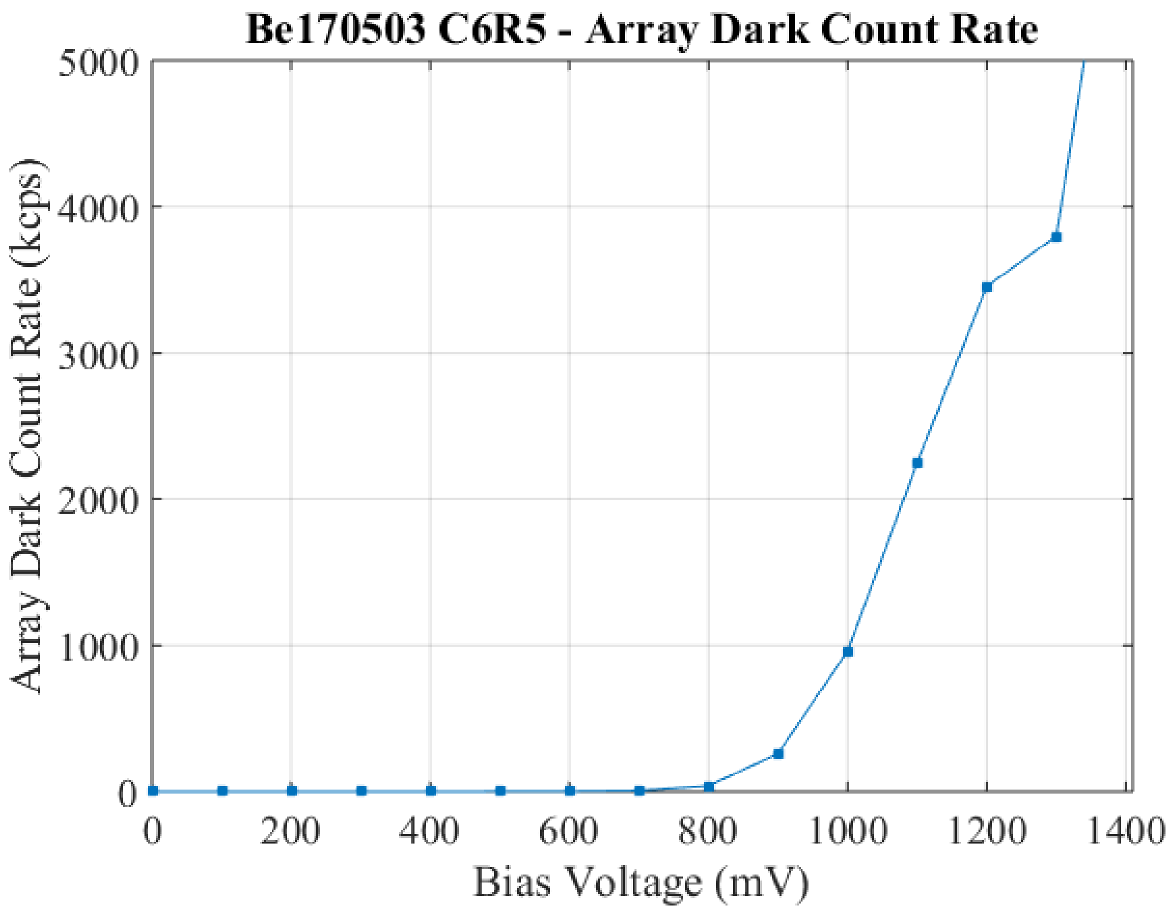




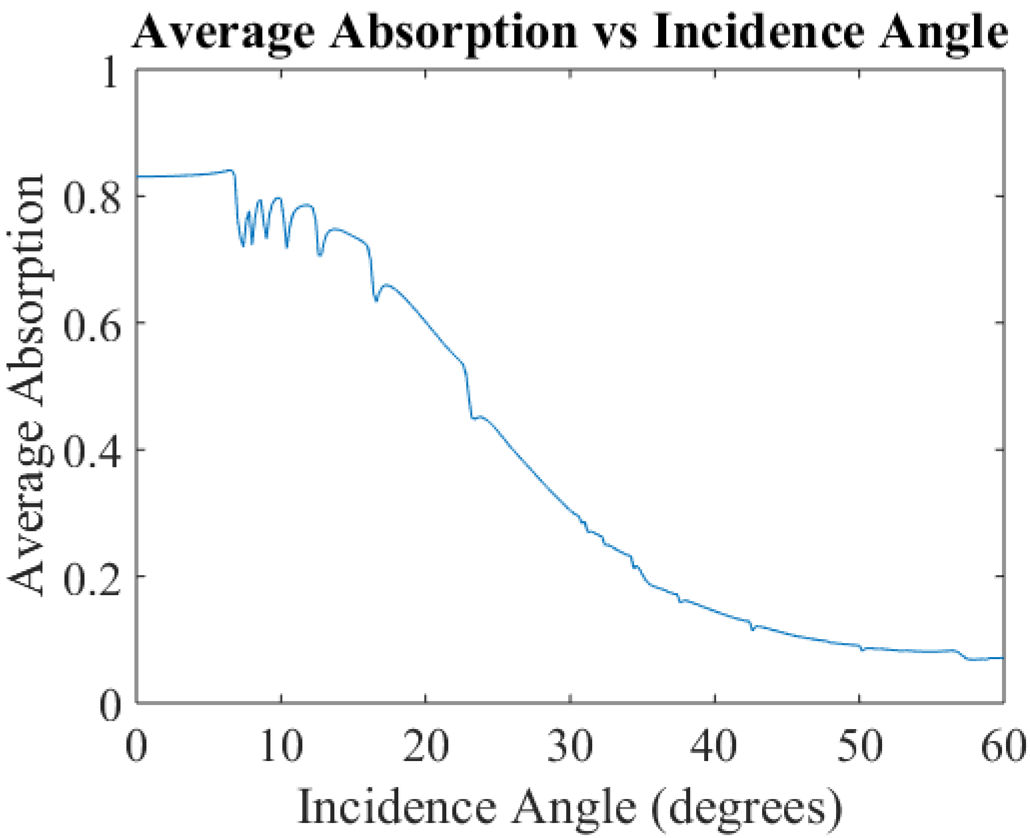
False Count Rate

Jet Propulsion Laboratory
California Institute of Technology

- 350 kcps at back of plateau – 3.8 Mcps at front of plateau
- Can implement cryogenic spatial filter and/or shortpass filter to improve this
- Engineering tradeoff between false counts and efficiency

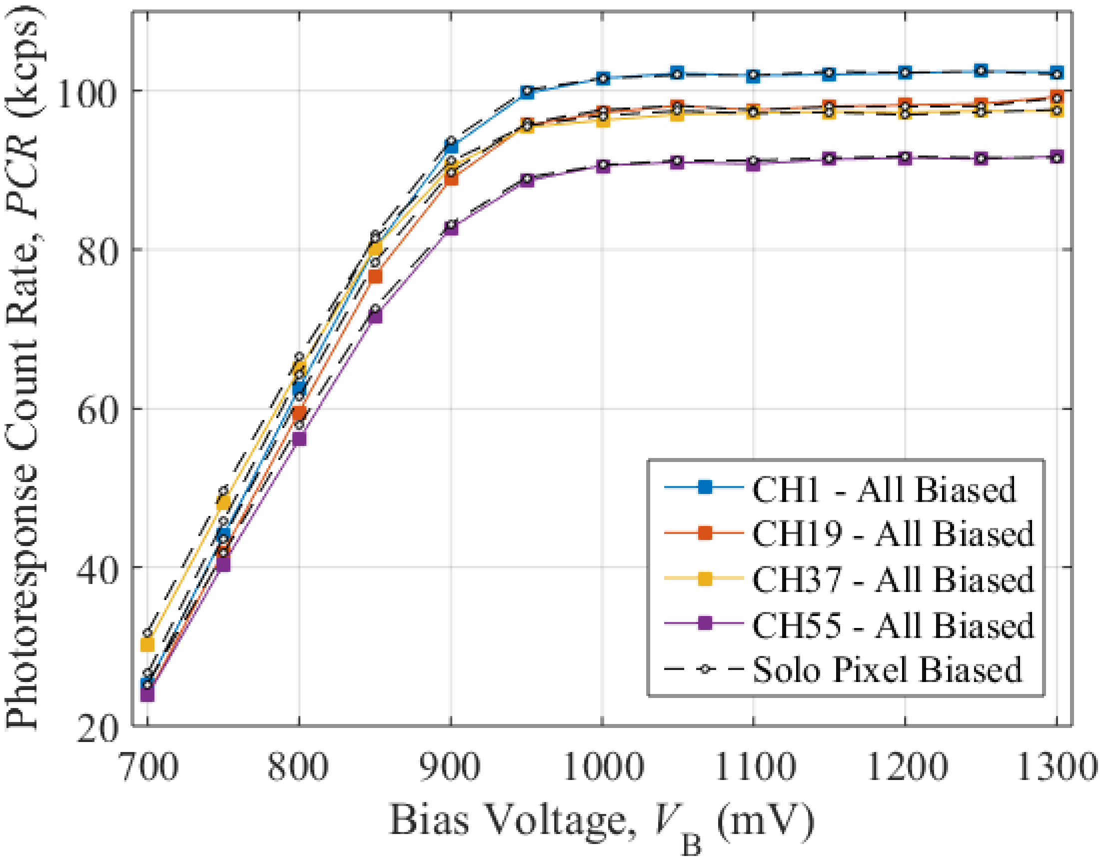


Angular Acceptance of Detector



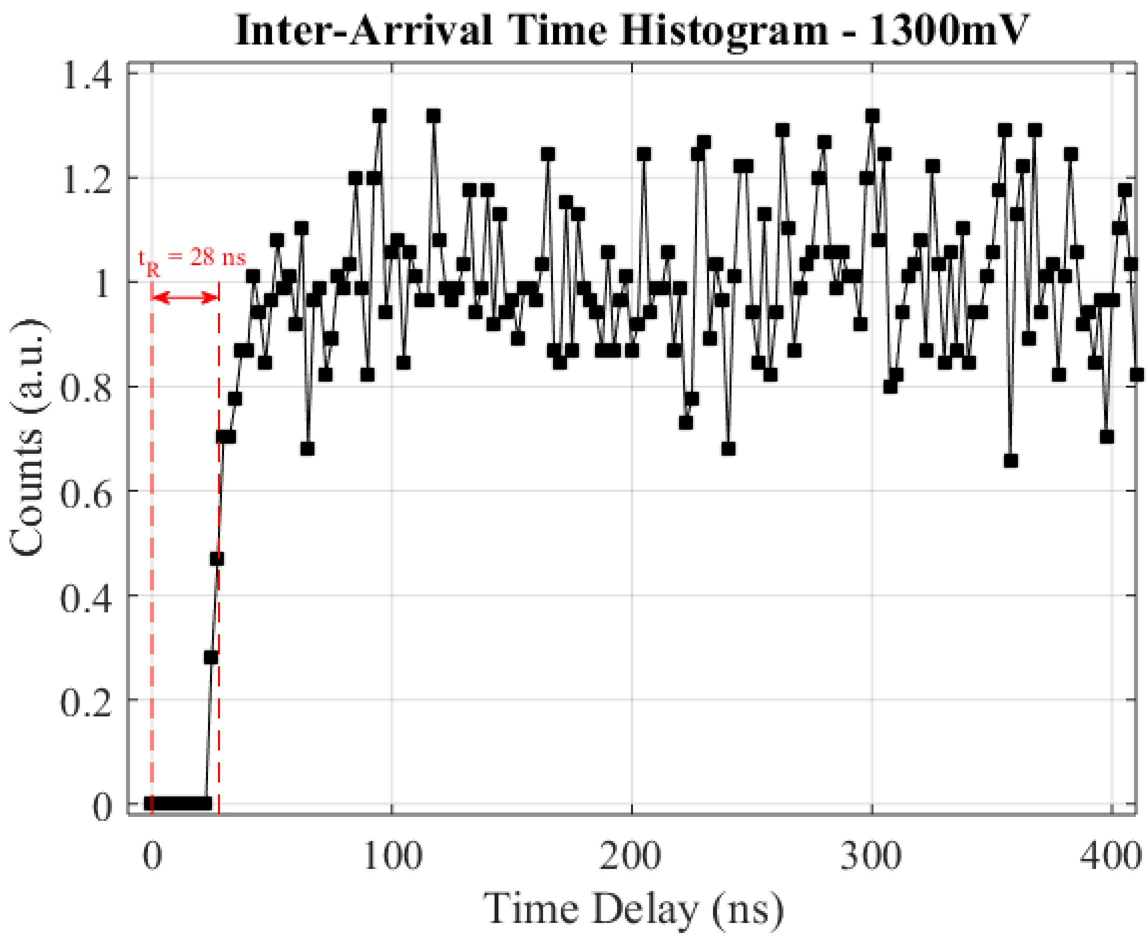
- RCWA simulations predict that optical stack limits angular acceptance of detector
- 3 dB point is at a half-angle of 26 degrees
- Resonances are due to diffraction effects, break azimuthal symmetry

Absence of Crosstalk



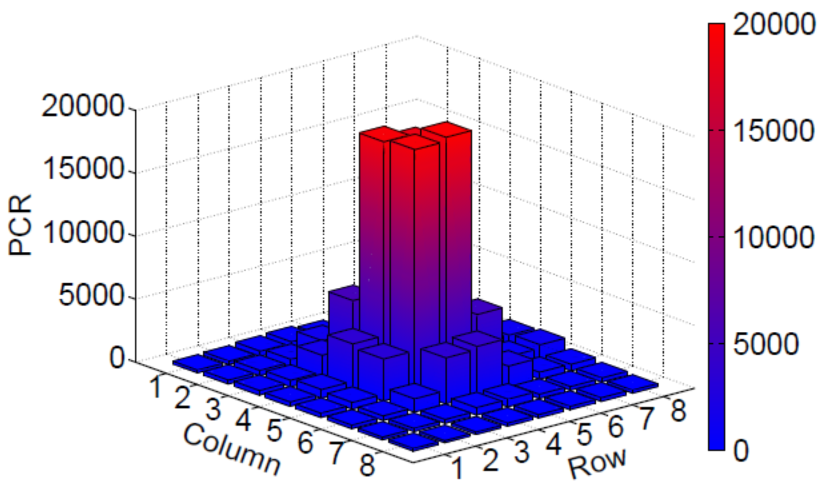
- No crosstalk is observed with 1200 nm pitch co-wound arrays
- Severe crosstalk was observed with 320-800 nm pitch co-wound arrays
- From scaling, crosstalk is believed to be thermal
- Physics of crosstalk is under study with a generalized electrothermal model

Absence of Afterpulsing

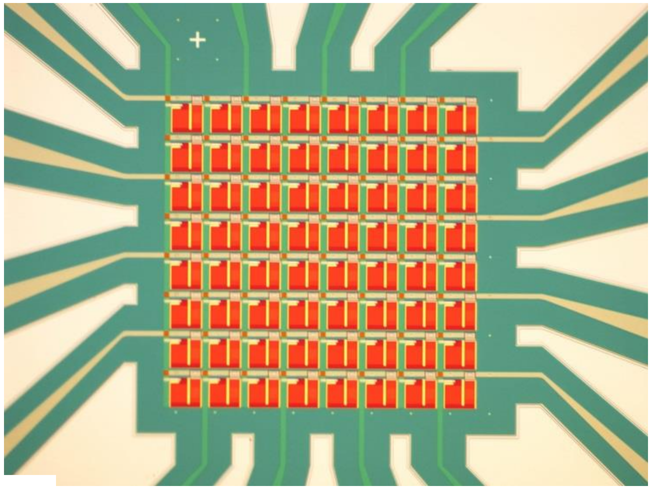


- Interarrival time histogram shows no presence of afterpulsing
- Recovery time is 28 ns

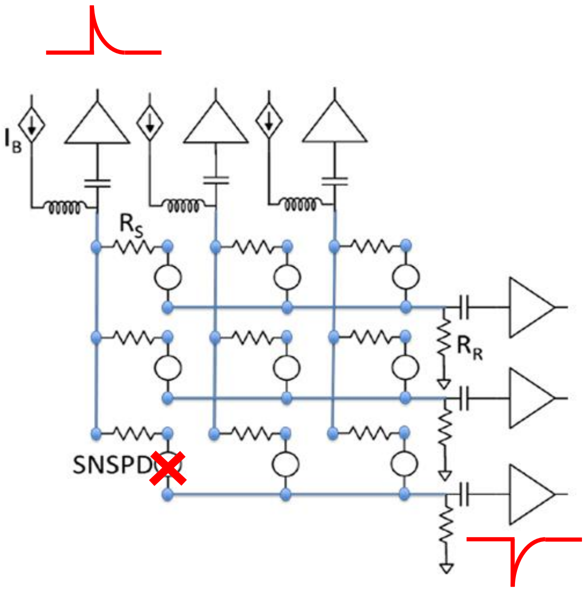
64 Pixel "Row-Column" Arrays



- 64 pixel (8 x 8) sparse WSi SNSPD array for fast time-correlated imaging
- Row-Column readout strategy allows 64 pixels to be read out using 16 lines
- Kilopixel Row-Column arrays are "low-hanging fruit" with 64-channel readout



8x8 Array at 1550 nm

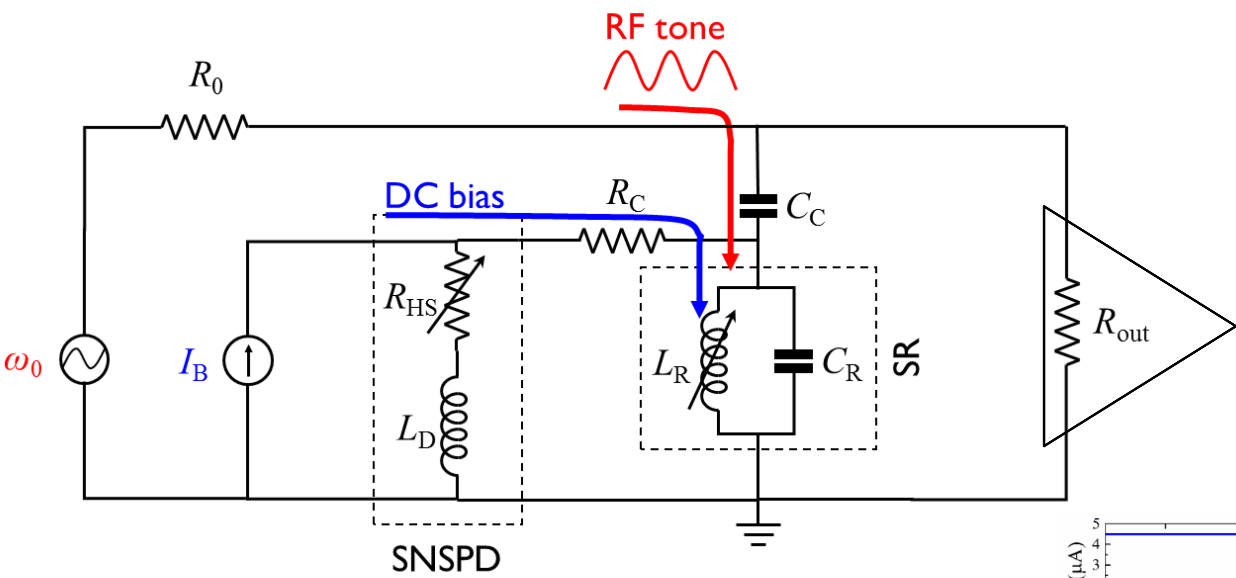


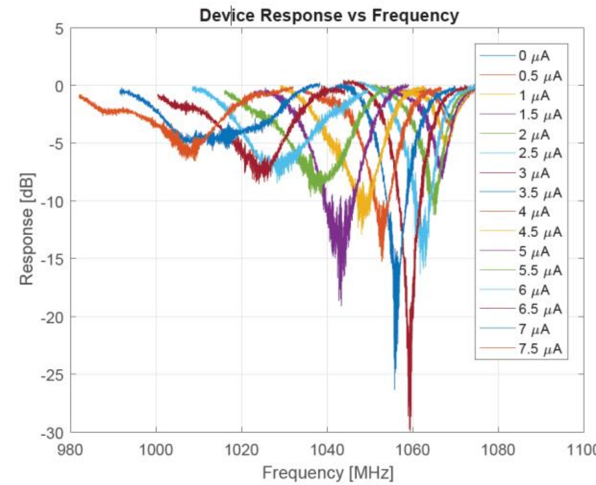
Operating Concept

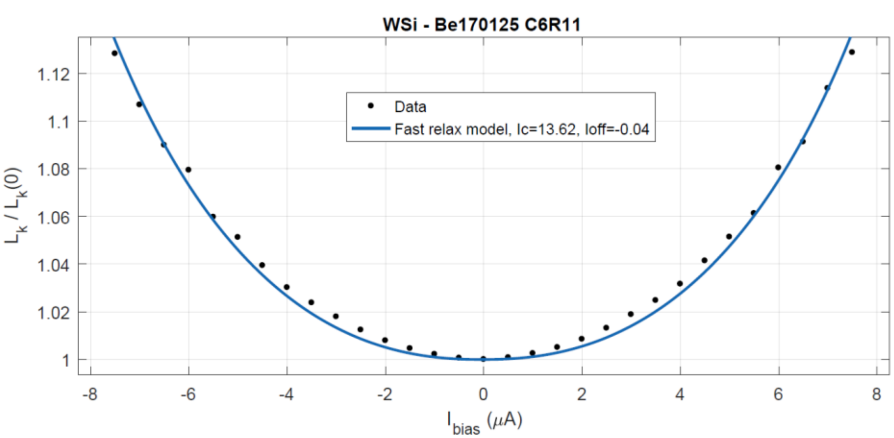
Allman et al, APL (2015)

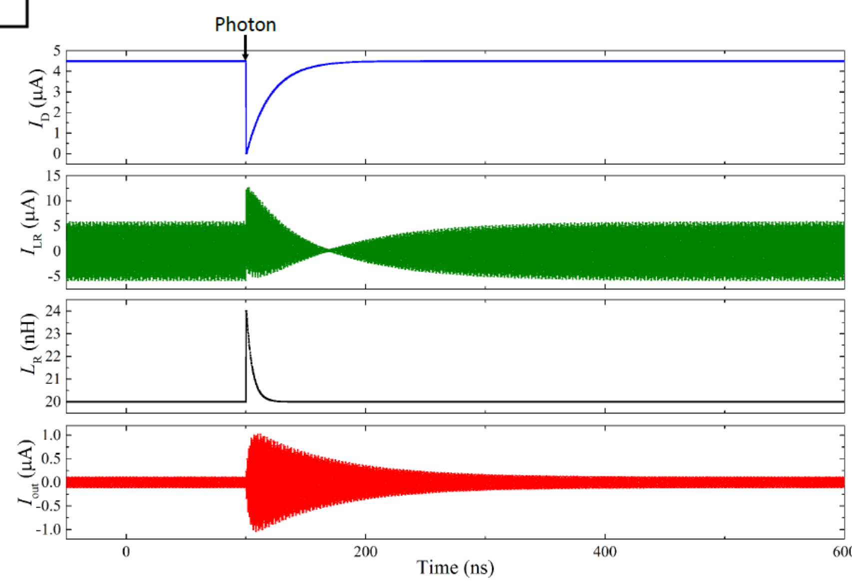
Frequency Multiplexed SNSPDs

- Superconducting Microwave Resonators used to read out SNSPDs
- Scalable to >1000 pixels per RF feedline

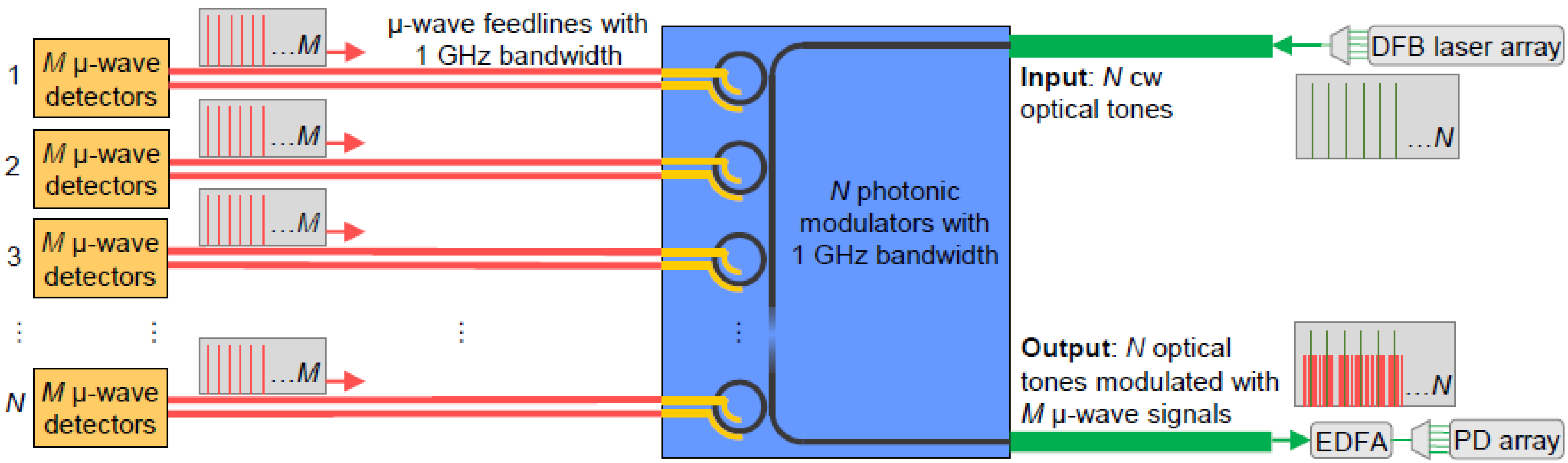








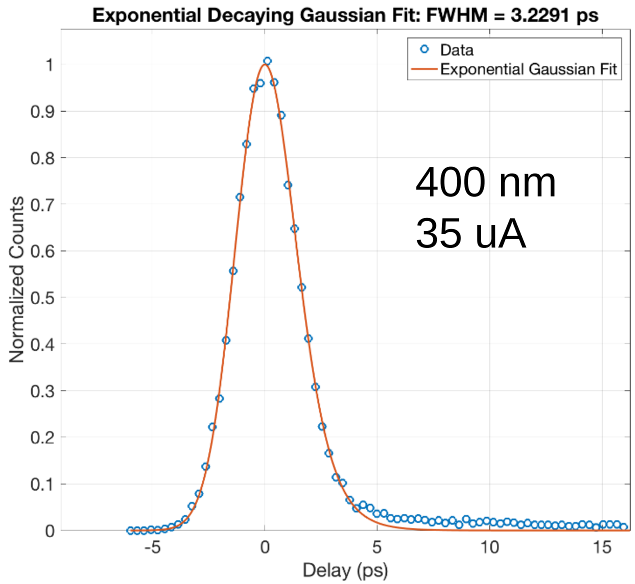
Optical Multiplexing Strategies

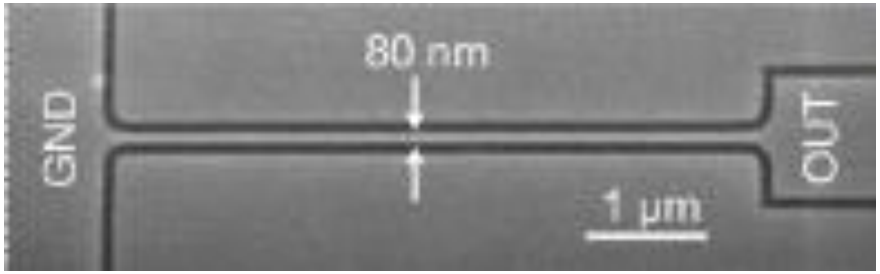


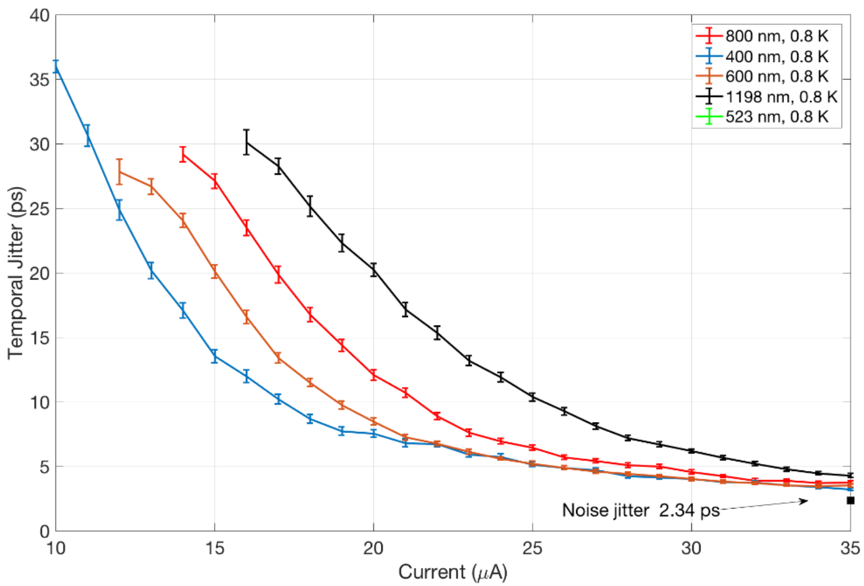
- Superconducting Microwave Resonators read out superconducting detectors
- Use cryogenic optical modulator to encode many “banks” of RF tones onto an optical carrier
- Scalable pathway to get megapixel-class superconducting camera data out of a sub-kelvin cryostat
- Especially relevant for Far-IR and deep UV astrophysics applications

Ultra High Time Resolution SNSPDs

- Single photon detection with 3.2 ps FWHM time resolution achieved at 400 nm and 4.8 ps FWHM jitter at 1550 nm
- Specialized SNSPD with low-noise cryogenic amplifier readout
- 5 µm x 120 nm x 5 nm NbN nanowire
- Still limited by instrumental mechanisms at lowest jitter – have not yet reached fundamental limits
- Intrinsic jitter mechanism is now accessible for study
- Low jitter in devices with larger active area is practical using differential readout

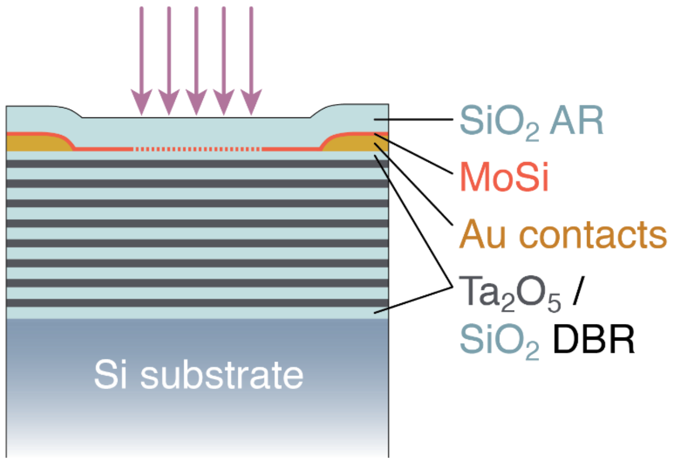


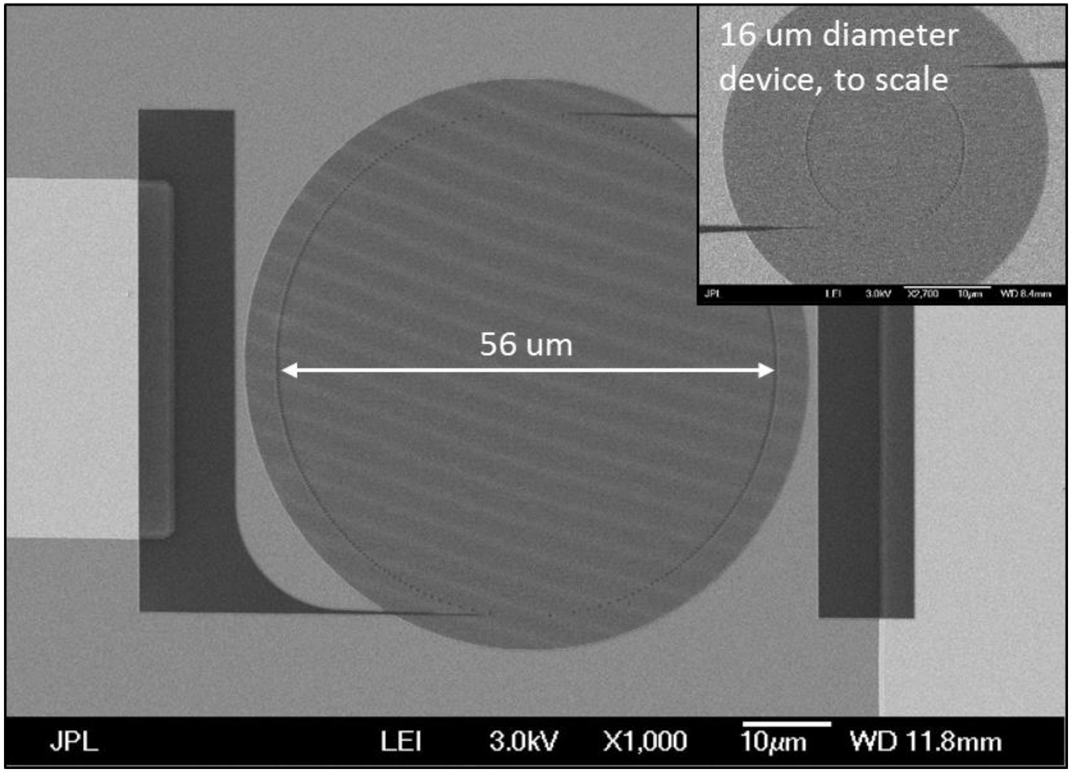




Ultraviolet SNSPDs

- Fiber-coupled MoSi UV SNSPDs for applications in ion trap quantum computing
- 80% Efficiency at 370 and 315 nm, single photon sensitivity at 245 nm
- DBR mirrors to enhance absorption
- 4.2 K operating temperature
- mHz dark count rates when coupled to optics, < 7e-5 cps intrinsic dark count rates

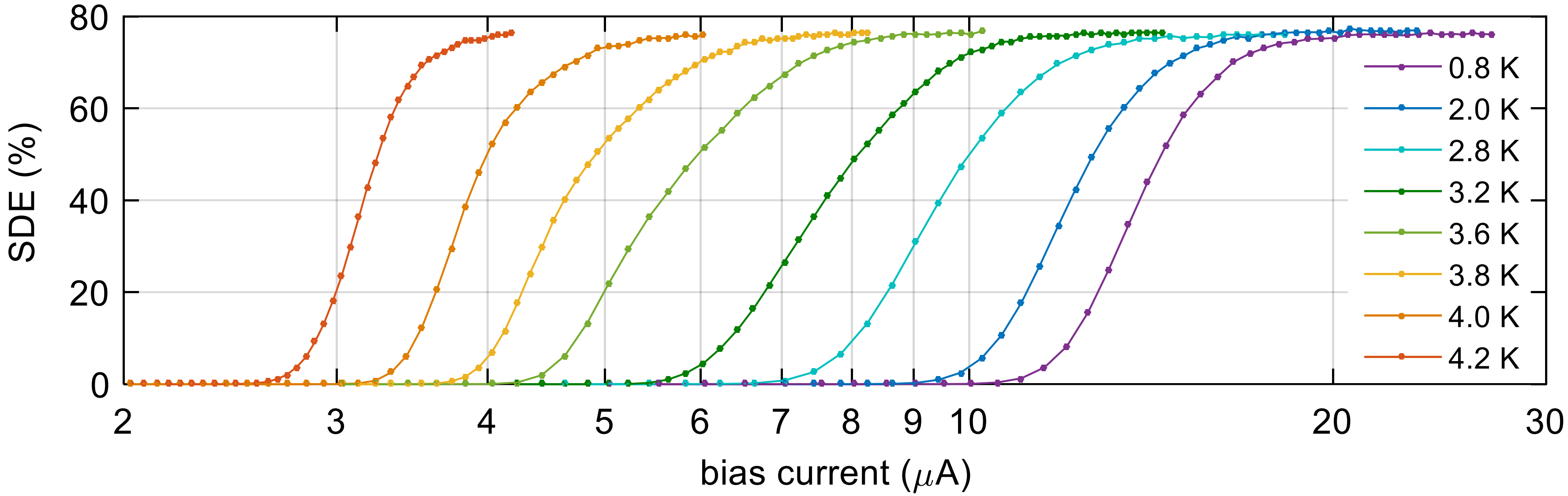


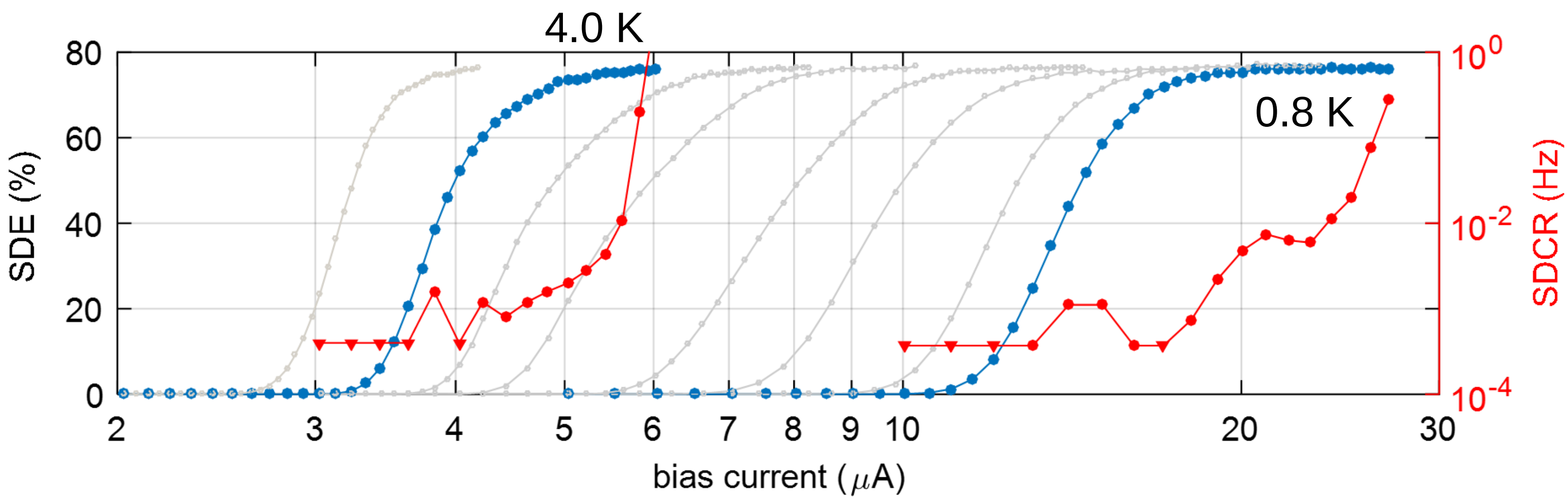


NIST

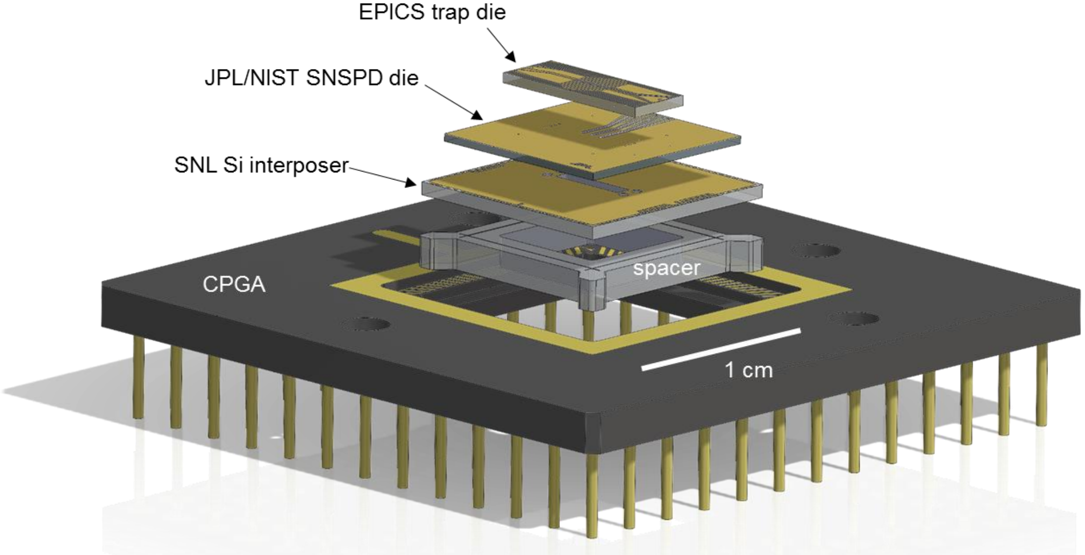
Efficiency and Dark Counts at 370nm

Jet Propulsion Laboratory
California Institute of Technology

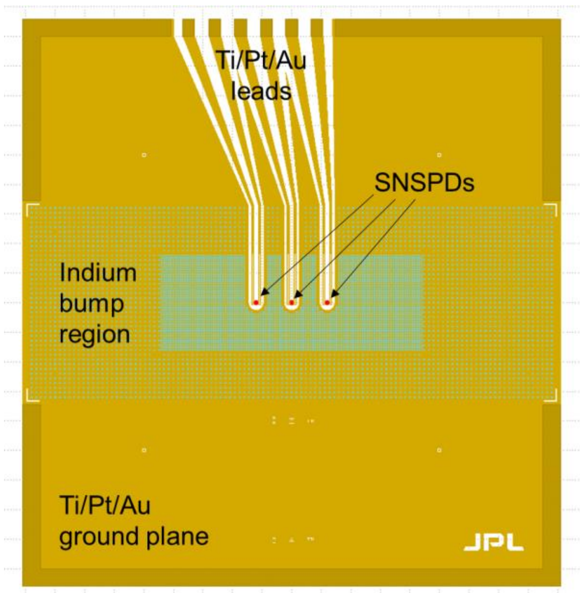


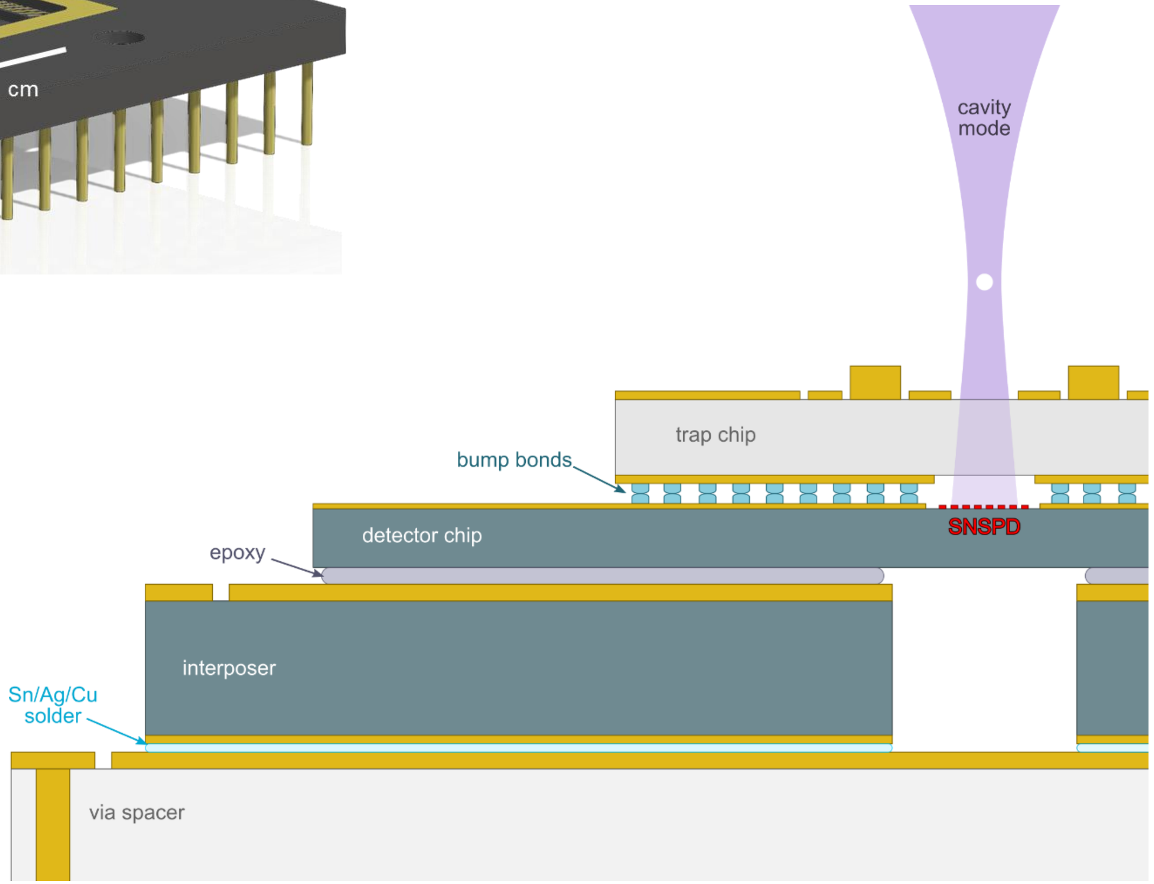


Integration with Ion Trap Chips



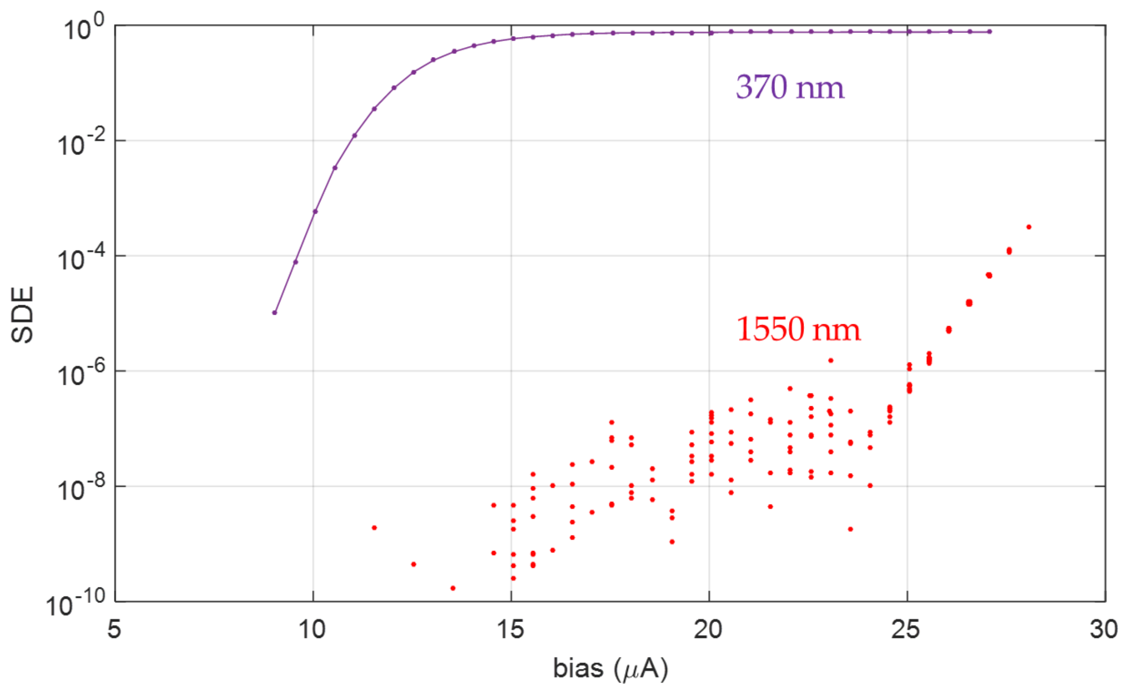
- Hybrid integration between ion trap chips and free-space UV SNSPDS
- Collaborative effort between JPL, NIST, Sandia, and Duke University





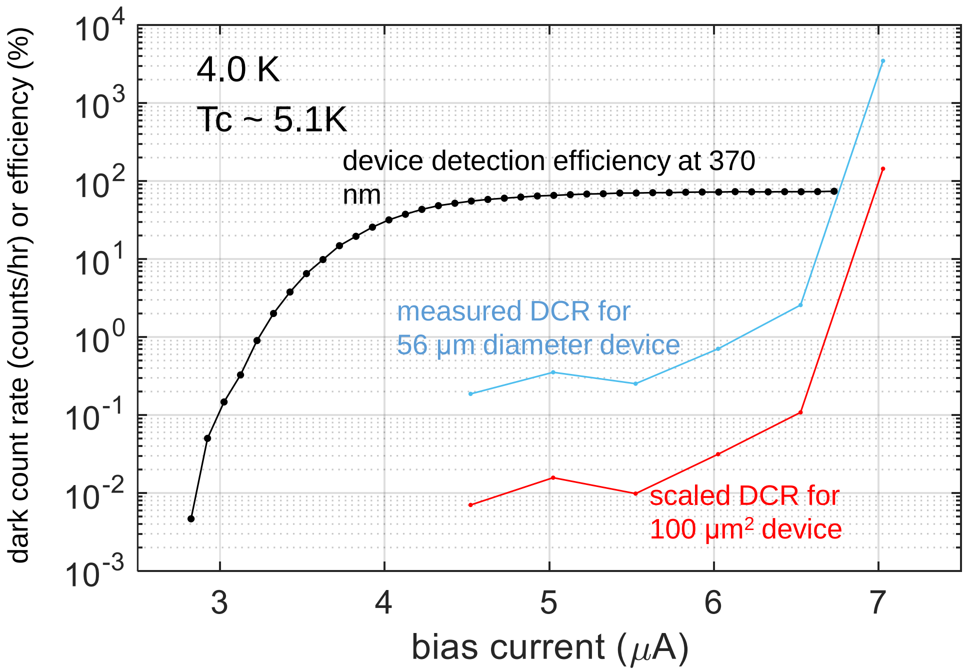
Intrinsic SNSPD Dark Counts

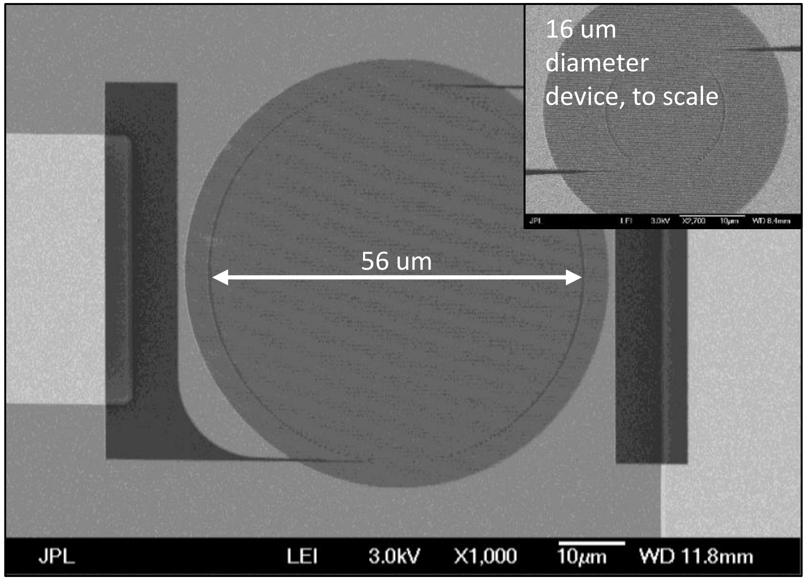
- SNSPDs optimized for high efficiency in the NIR are limited by thermal blackbody
- False count rate determined by spatial and spectral filtering
- UV SNSPDs are blind to IR, ideal for studying intrinsic false counts
- False counts $<10^{-3}$ cps at 70% SDE coupled to fiber
- 56 µm diameter active area coupled to 50 µm core fiber



Intrinsic SNSPD Dark Counts

- To improve the statistics, returned to larger active area devices (56 μm diameter)
- Performed false count measurements at 4 K without coupling to fiber
- Each point integrated for 10 hours
- Measured 7e-5 cps (6 counts per day) on large-area device at 4 K
- If DCR scales with active area, 10 x 10 μm pixel would have 3e-6 cps (88 counts per year)

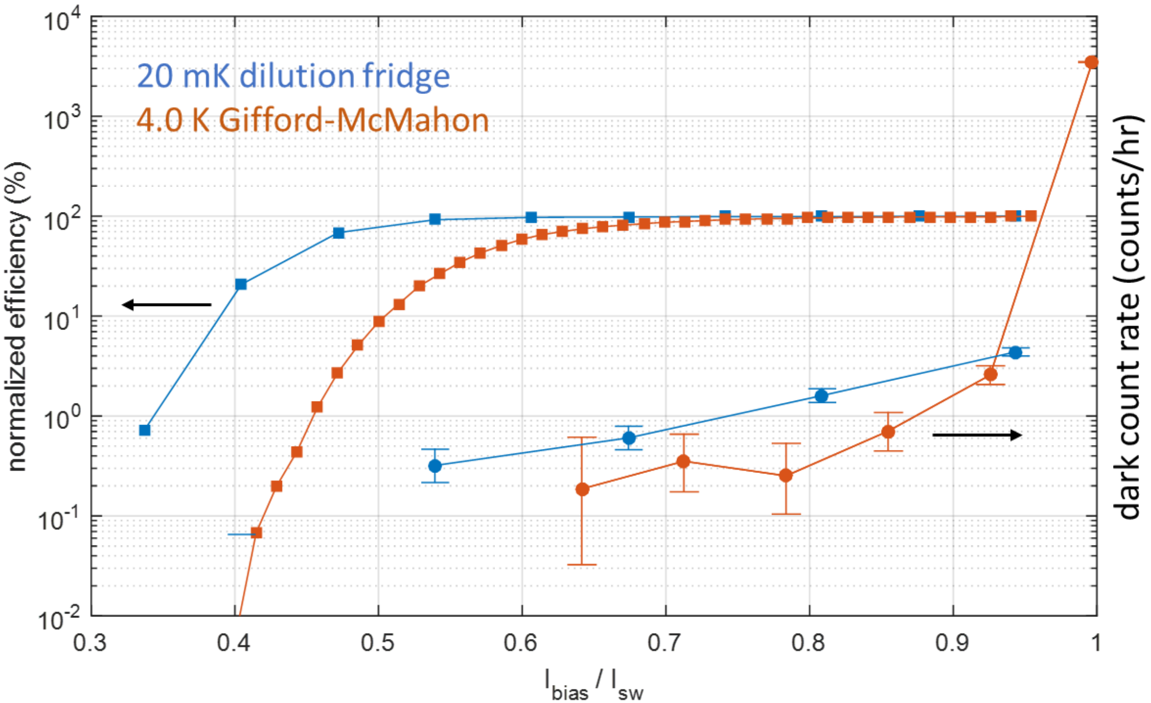




Intrinsic SNSPD Dark Counts

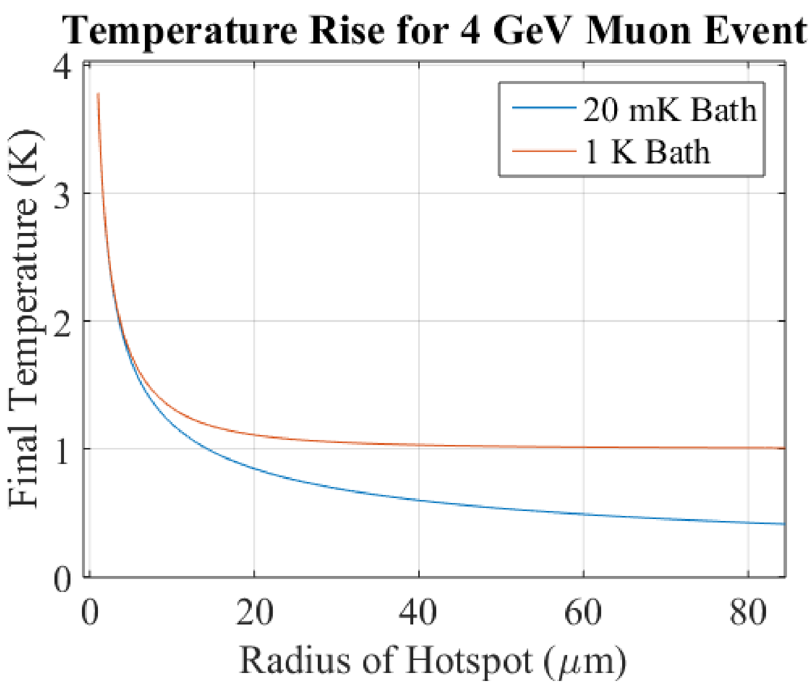
Jet Propulsion Laboratory
California Institute of Technology

- Measured 56 µm device in a heavily shielded dilution refrigerator at 20 mK
- Illuminated with cryogenic UV LED at 4 K, integrated 28 hours per point
- False counts at 20 mK comparable to 4.0 K in less well shielded system
- Would expect temperature dependence for intrinsic dark counts

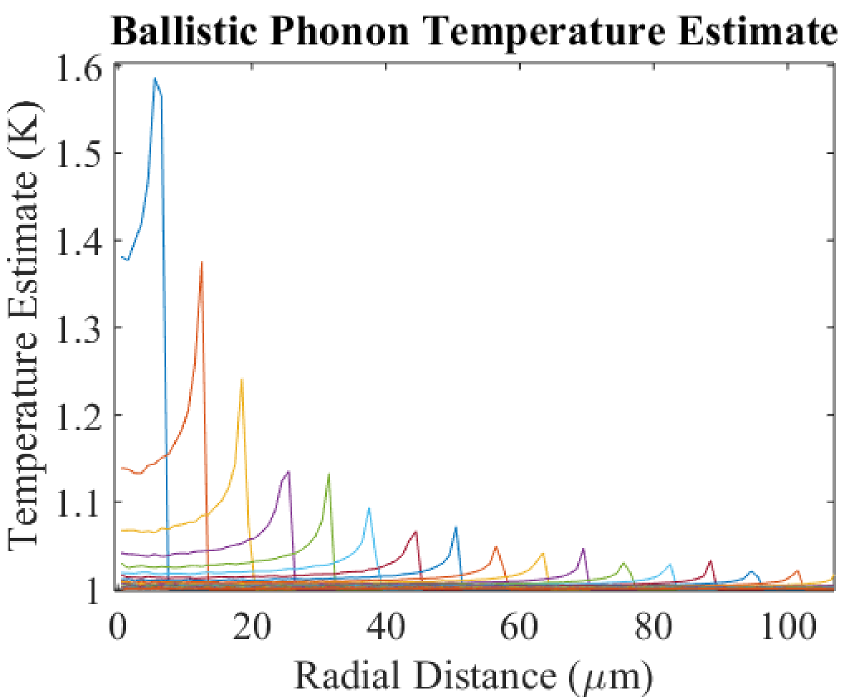


Predicted Cosmic Ray Limits

- At sea level, muons are the dominant contribution to cosmic ray flux
- Integrated flux rate 0.0148 muon / cm^2 / second, average energy 4 GeV
- Modeled thermal transport in Si, found < 10 µm sensitive region beyond active area
- For 60 µm diameter detectors needed to couple efficiently to 1-m telescope, muon count rate is 5.7e-8 cps – much lower than observed count rates

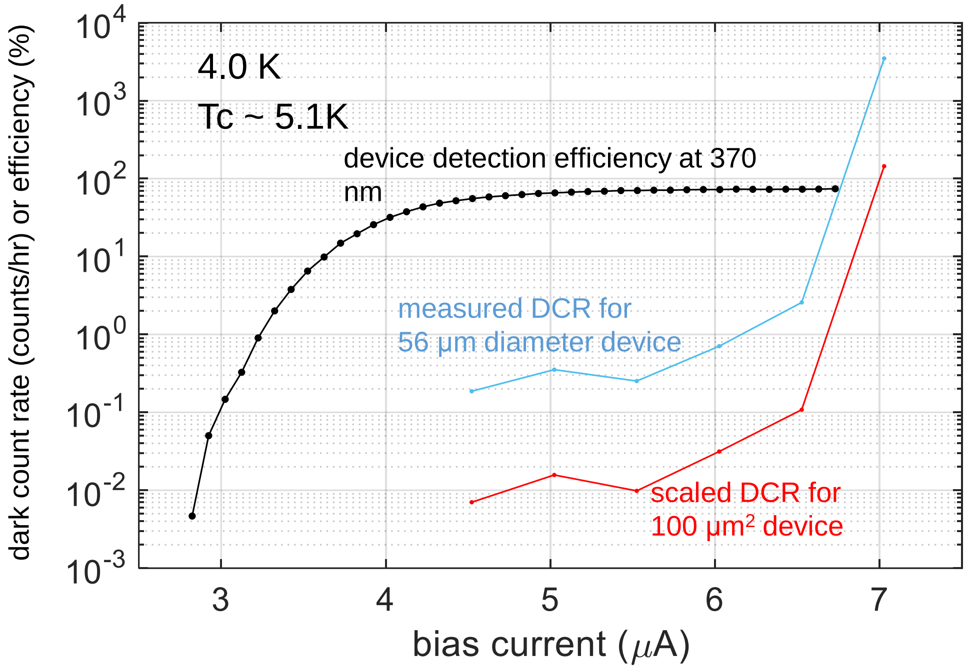


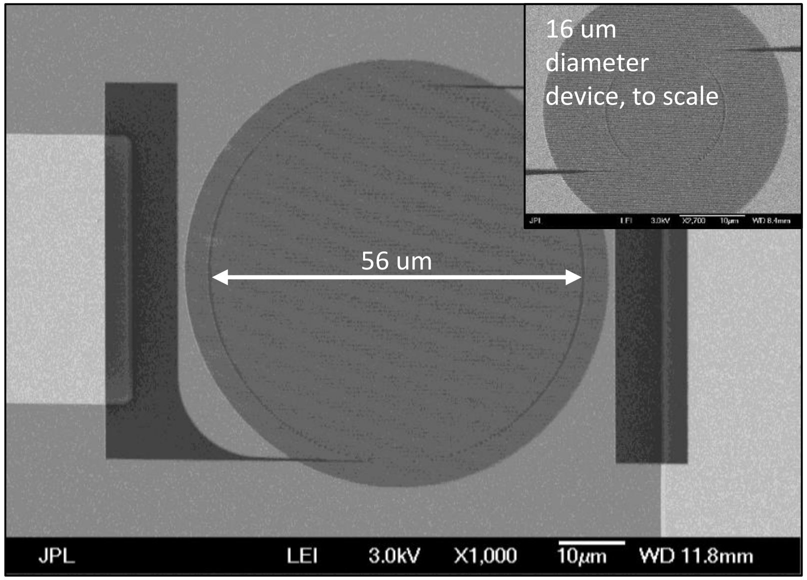
Simple Cylindrical Hotspot Model



Monte Carlo Thermal Transport Model

Ultra Low Dark Counts for UV SNSPDs

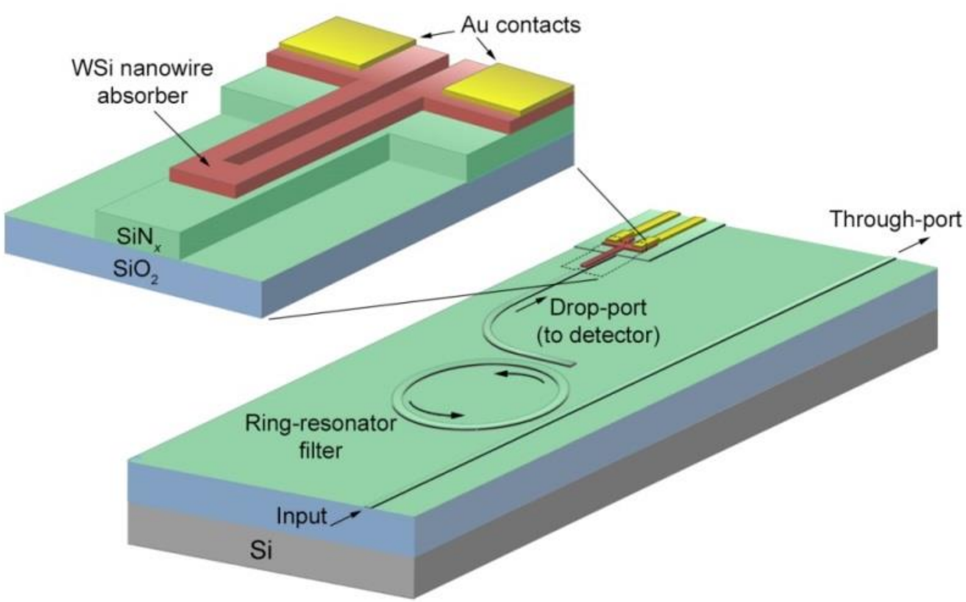


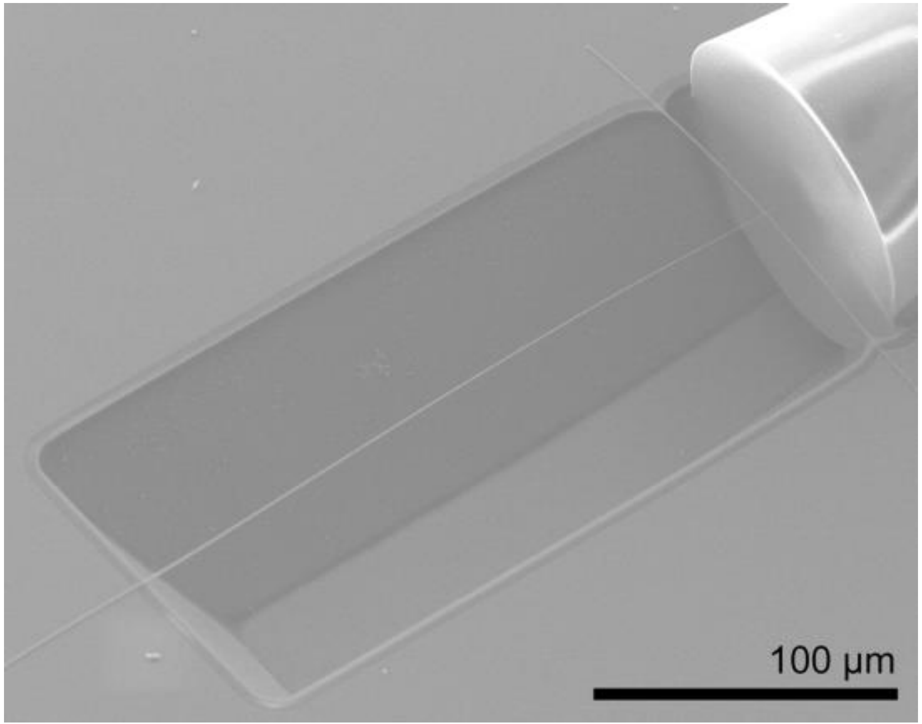


- 10 nm thick, 110 nm wide MoSi wire optimized for high efficiency (76%) at 370 nm
- UV SNSPDs have > 70 dB blindness to IR wavelengths, eliminating thermal background
- Measured 7e-5 cps (6 counts per day) on large-area device at 4 K
- If DCR scales with active area, 10 x 10 µm pixel would have 3e-6 cps (88 counts per year)

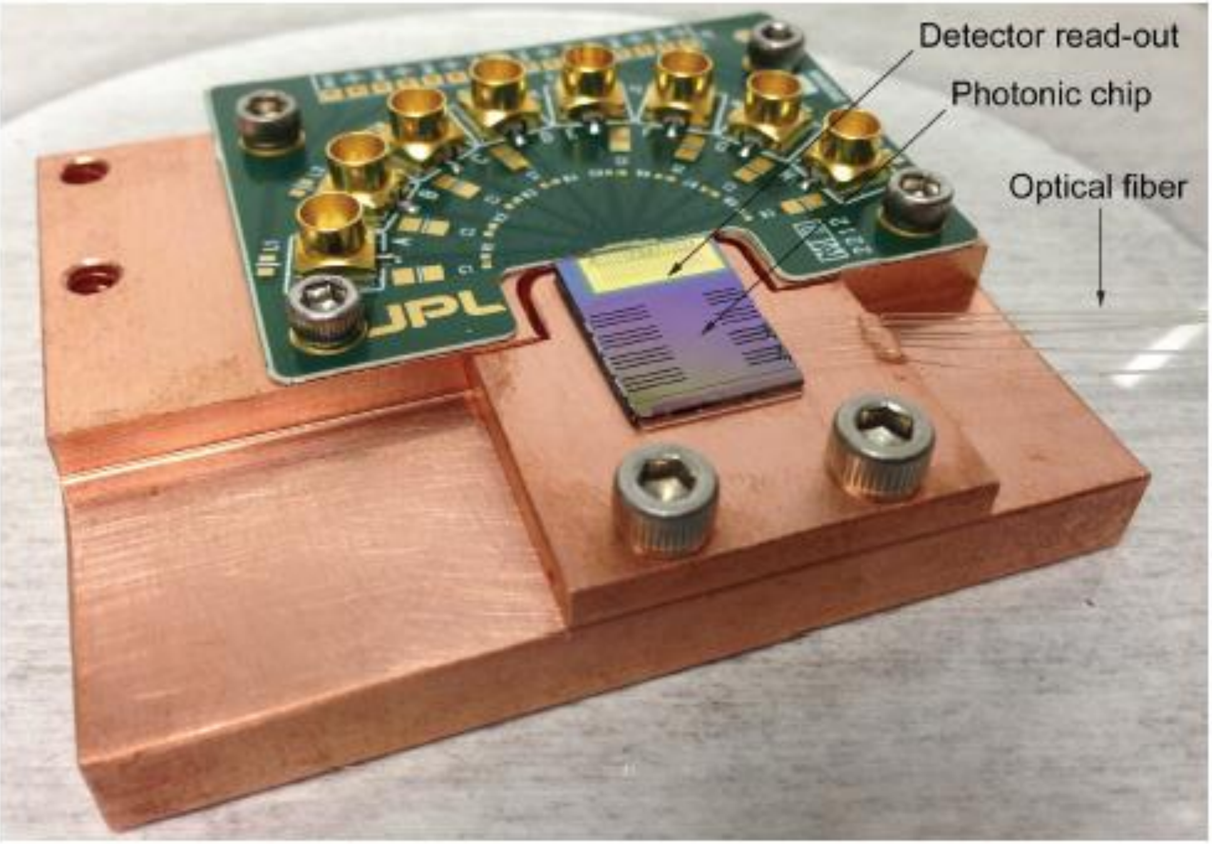
On-Chip Integrated SNSPDs

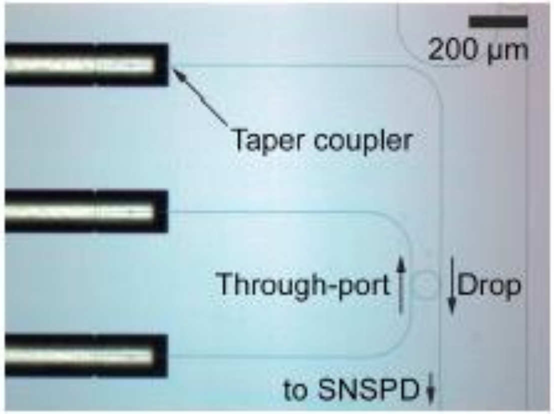
- WSi SNSPDs coupled to SiN waveguide photonics platform
- Integration with low-loss broadband optical couplers (Collaboration w/ Painter Group, Caltech)
- Integration with on-chip ring resonators or echelle grating to form channelizing spectrometer or DWDM receiver for QKD
- Can realize a robust, on-chip cryogenic spectrometer, particularly in the mid-IR
- Promising preliminary results

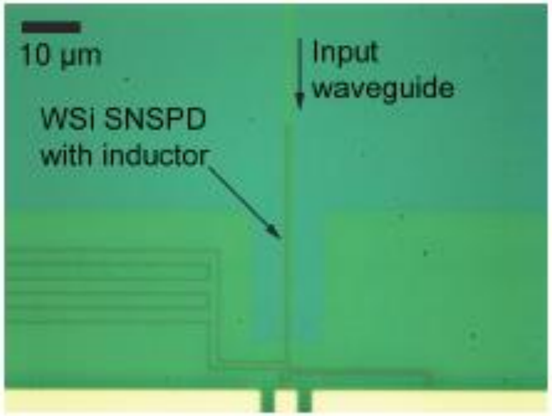




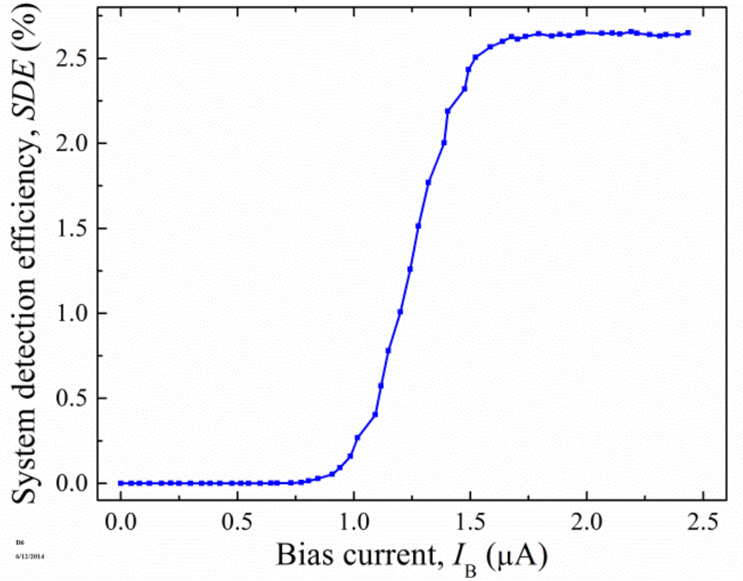
On-Chip Integrated SNSPDs

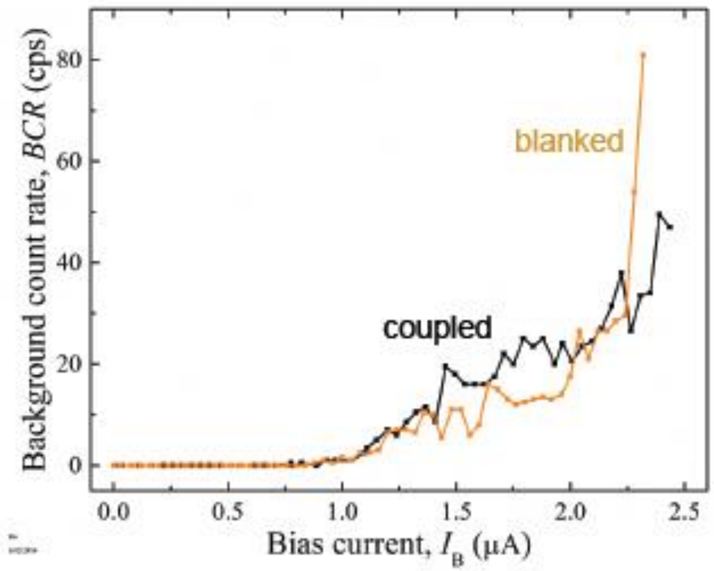


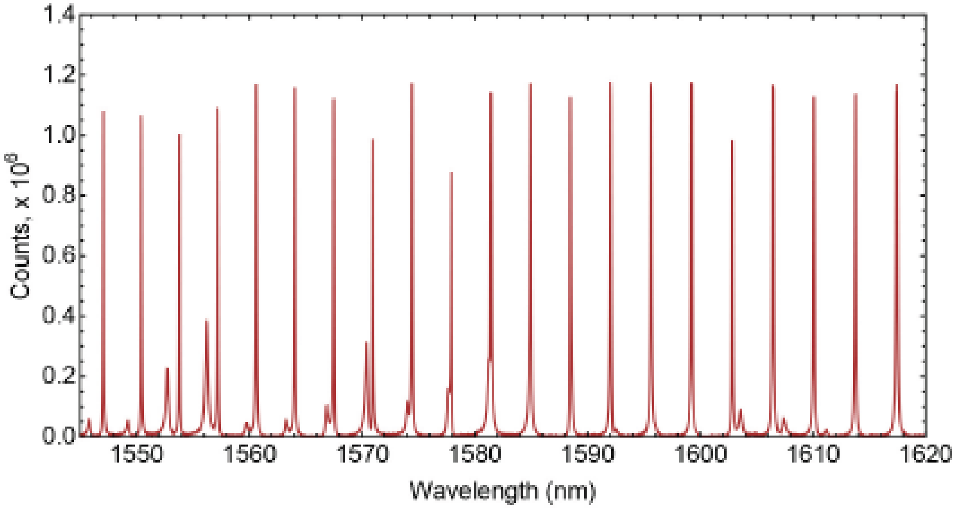


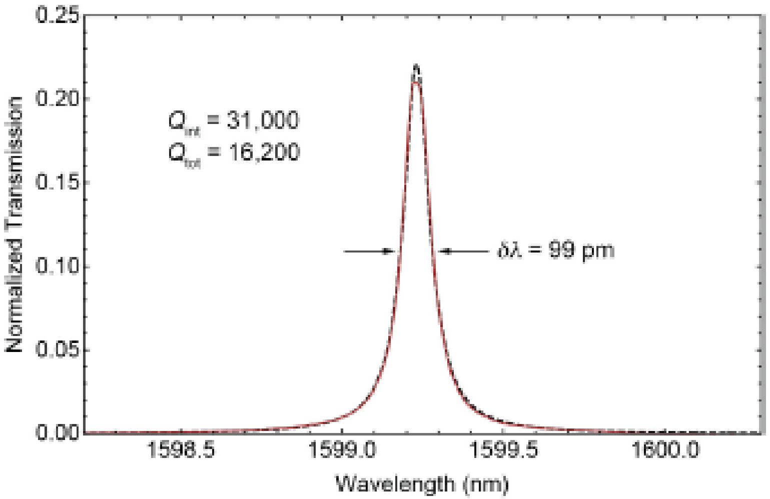


On-Chip Integrated SNSPDs







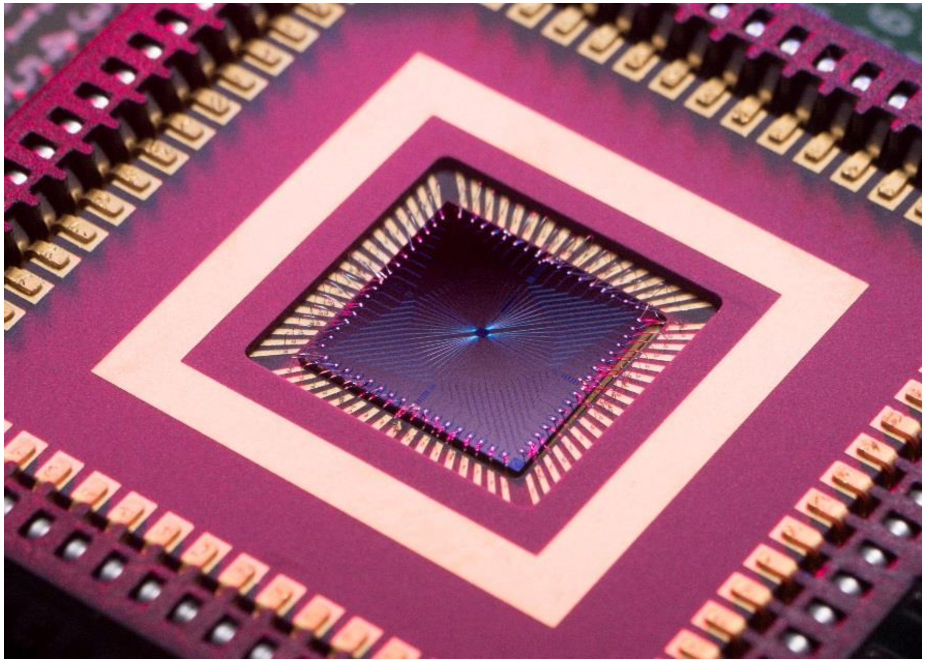


Future Directions for Waveguide SNSPDs

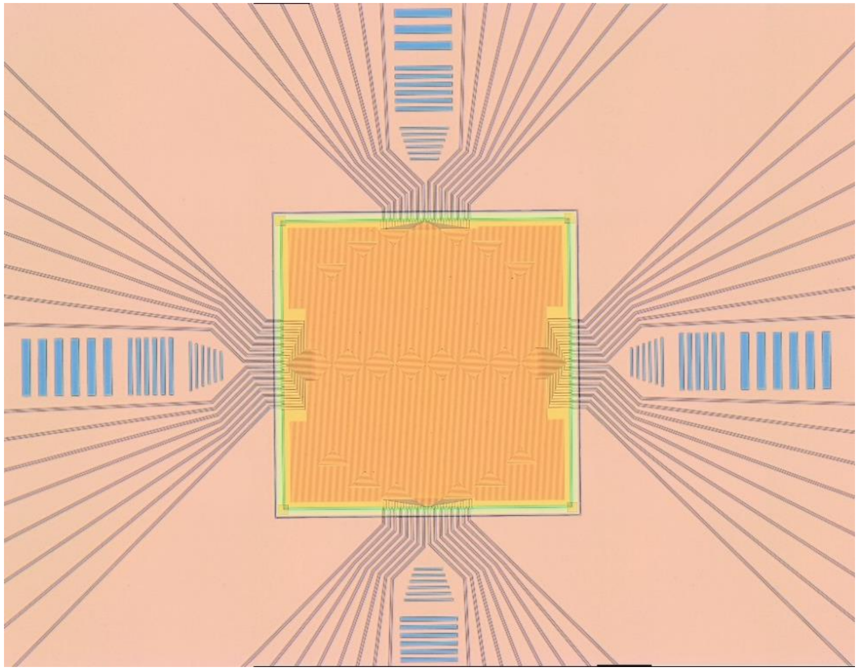
- Single-mode receivers behind AO systems
  - Integrated photonics is well suited to one or few spatial modes
- Ultra-low jitter optical communication receivers
  - Waveguide devices can be very short, reducing geometric jitter
- Frequency demultiplexing receivers
  - Integrated photonics is well suited to on-chip spectrometers, AWGs
- Ultra-high count rate receivers
  - Trees of low-loss beamsplitters can be used to feed light to SNSPDs
- Advanced receiver schemes
  - "Green Machine" can be implemented in photonic nanoprocessors
  - Gives information efficiency of PPM while alleviating peak-to-average power requirements on the transmit laser.
- On-chip heralded single photon sources
  - Relevant for space-to-ground quantum communication experiments

Conclusions

- SNSPDs are the highest performing detectors available for time correlated single photon counting
- Deep cryogenic operating temperatures make them best suited for the ground
- Progress in performance has been extremely rapid
- Technology is very new, with many opportunities for new innovation
- Fully compatible with integrated photonics



64-pixel SNSPD array mounted in chip carrier



Optical microscope image of array

NIST